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An intensive chemical and biological survey of Liberty Bay, Washington, was launched by EPA, Region X, in September, 1975, following reports of heavy metal contamination of the Bay's surface waters. The survey was designed to obtain information on levels of heavy metals and other possible toxicants in seawater, wastes, sediments, fish and shellfish from selected sites in Liberty Bay and other Puget Sound waters. Also sought was toxicological data on the acute effects of those waters and sediments on the development and survival of embryos of the Pacific oyster, Crassostrea gigas.

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CHEMICAL AND BIOLOGICAL SURVEY OF LIBERTY BAY, WASHINGTON

by

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REGION X
SURVEILLANCE AND ANALYSIS DIVISION
SEATTLE, WASHINGTON 98101

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Special thanks go to the Coast Oyster Company and to the many private property owners who granted us permission to collect shellfish samples from their beaches.

INTRODUCTION

An intensive chemical and biological survey of Liberty Bay, Washington was launched by EPA, Region X in September, 1975 following reports of heavy metal contamination of the Bay's surface waters.

Concentrations of total mercury ranging from <1 ug/l to as high as 110 ug/l were reportedly measured in Liberty Bay seawater by a commercial testing laboratory in conjunction with a privately financed water quality investigation. The investigation was initiated by Sea Farms, Inc., an oyster hatchery located in Poulsbo, Washington. The hatchery's interest in the chemistry of Liberty Bay seawater stemmed from its basic need for water of high quality coupled with its desire to identify the cause of mortalities of Pacific oyster embryos and larvae experienced at various times since it began using Liberty Bay water in July, 1973.

During the period Sea Farms was plagued most heavily with larval mortalities (October 1974 - August 1975) it began to suspect and investigate several activities associated with the Bay as being possible sources of the problem. These activities included the hatchery operation itself, as well as the discharge of wastes from the Poulsbo sewage treatment plant, the dredging of the Poulsbo marina in the spring of 1975, and the discharge of metal-laden wastes from the Navy's Keyport Torpedo Station. After reporting the results of the investigation, Sea Farms closed the hatchery in August, 1975, believing that mercury and possibly other metal contaminants were responsible for the recurrent mortalities of the young oysters.

Purpose

The EPA survey was initiated to quickly obtain information on the levels of heavy metals and other possible toxicants in seawater, wastes, sediments, fish, and shellfish from selected sites in Liberty Bay and other Puget Sound waters. The investigation was also designed to provide toxicological data on the acute effects of these waters and sediments on the development and survival of embryos of the Pacific oyster, *Crassostrea gigas*. This descriptive information was needed to achieve the following objectives:

1. Determine if Liberty Bay was seriously contaminated with mercury or other metals as reported,
2. Identify and locate possible sources of such toxicants, thus providing evidence supporting required pollution control or enforcement actions,
3. Provide public health officials with information on which to base decisions concerning the harvesting and consumption of fish and shellfish from the Liberty Bay area, and
4. Elucidate the role of Liberty Bay water quality in the reported mortalities of Pacific oyster embryos and larvae.

SUMMARY

(Findings and Conclusions)

1. A history of continuous or intermittent mercury contamination in Liberty Bay of the magnitude reported by Sea Farms, Inc., would undoubtedly have had an adverse effect on oyster embryos and larvae in addition to seriously contaminating a variety of marine organisms of ecologic and economic value. However, no major sources of mercury or serious mercury contamination were found during the survey. Total mercury concentrations in Liberty Bay seawater were similar to those measured in east-central Hood Canal - an area considered to be relatively free of industrial pollutants. The concentrations of mercury measured in marine organisms from the Bay also suggested that serious mercury contamination was not a persistent problem. Mercury levels in edible tissues of fish and shellfish collected from Liberty Bay were below the proposed FDA Action Level of 0.5 ug/g (wet weight) for mercury in seafoods.

2. Elevated concentrations of mercury and several other metals were measured, however, in sediments from several Liberty Bay sites. This apparent contamination was believed to reflect inputs of metallic wastes to the Liberty Bay system resulting from inadequate industrial and domestic waste treatment.

3. The Navy Torpedo Station was found in violation of its National Pollution Discharge Elimination System (NPDES) permit. Sea Farms, Inc. and the City of Poulsbo's sewage treatment plant were found in violation of the Federal Water Pollution Control Act (P.L. 92-500) for discharging wastewater to Liberty Bay without a permit.

4. Estimates of the impact of continuous and intermittent bypasses of untreated metal plating waste from the Navy Torpedo Station to Liberty Bay indicated these sources would produce some increase in the seawater concentrations of cadmium, chromium, and nickel. However, resulting metal levels at the Sea Farms hatchery site would not have exceeded concentrations suggested by the National Academy of Sciences (1972) as being hazardous in the marine environment. The combined contribution of bypasses of these and other metals by the Torpedo Station was also estimated not to have exceeded a hazardous level at the Sea Farms site.

5. The relative toxicity to oyster embryos of treated effluents from local sewage treatment plants followed the order: Poulsbo > Navy Torpedo Station > Keyport. Dilution simulations indicated that under certain conditions treated effluent from the Poulsbo plant may have been toxic to oyster embryos and larvae when it reached the Sea Farms hatchery site.

6. Most Liberty Bay waters and sediments collected during the survey were not acutely toxic to Pacific oyster embryos during 48 hour exposure periods. The larval mortalities and abnormalities that were observed in certain seawater samples were associated with an algal bloom occurring in the east-central portion of the Bay. The bloom was composed primarily of the dinoflagellates, *Gymnodinium splendens* and *Prorocentrum gracile*. Although related algae have been implicated in past mortalities of marine organisms, it was not known if these species were directly responsible for the toxic effects observed or if bacterial and fungal metabolites were involved.

7. Sediment toxicities appeared to be more closely related to total volatile solids concentrations in the sediments than to metal or sulfide levels. Although this observation suggested that certain organic constituents in the sediments were adversely affecting oyster embryos, its significance was not entirely understood.

8. The cause of the oyster embryo and larval mortalities experienced by Sea Farms, Inc. could not be determined. A few factors were identified, however, that probably contributed to the mortality problem, particularly when present in some combination with each other over an extended period. These factors included:

1. toxic metabolites of algal, bacterial, or fungal origin,
2. infectious diseases,
3. treated effluent from the Poulsbo sewage treatment plant, and
4. suspensions of sediments containing relatively high concentrations of metals, sulfides, volatile solids, and Pearl Benson Index (PBI)-sensitive substances.

Bypasses of metal plating wastes and other discharges from the Navy Torpedo Station were estimated not to have seriously impacted Liberty Bay water quality in the vicinity of the Sea Farms hatchery. It cannot be definitely stated, however, that past discharges of unknown volume and character would not have been toxic.

(Recommendations)

1. The conditions responsible for violations of the Federal Water Pollution Control Act and the National Pollution Elimination System that resulted in unpermitted discharges of metal plating waste, domestic sewage, and heated seawater to Liberty Bay should be corrected immediately. Certain corrective action has already been taken. Follow-up inspections should be conducted to assure that permanent elimination of these violations has been achieved.

2. The sewage treatment facilities of the City of Poulsbo should be improved to provide at least secondary waste treatment, with the outfall being located outside the Liberty Bay system.

3. Develop a program, in cooperation with other agencies, to chemically and biologically monitor water, sediments, and shellfish from selected stations in Liberty Bay, other Puget Sound areas, and the coastal zone. The primary purpose of such an effort would be to provide for the timely detection of environmental quality problems as well as improvements in quality associated with improved waste treatment practices.

4. Aquaculture activities, including oyster hatcheries, should only be located in areas having year-round supplies of high quality water. Site selection should be preceded by a comprehensive chemical and biological water quality evaluation to assure that this requirement is met.

5. The effects of selected algal, bacterial, and fungal metabolites on the development and survival of Pacific oyster embryos and larvae should be investigated.

6. Determine in more detail the factors affecting phytoplankton production in Liberty Bay, with emphasis on the possible stimulatory or inhibitory effects of sewage treatment plant discharges and metal plating wastes.

7. The individual and combined effects of metals and other potential toxicants on the development, survival, and growth of Pacific oyster embryos, larvae, and juveniles should be determined using long-term as well as short-term bioassays.

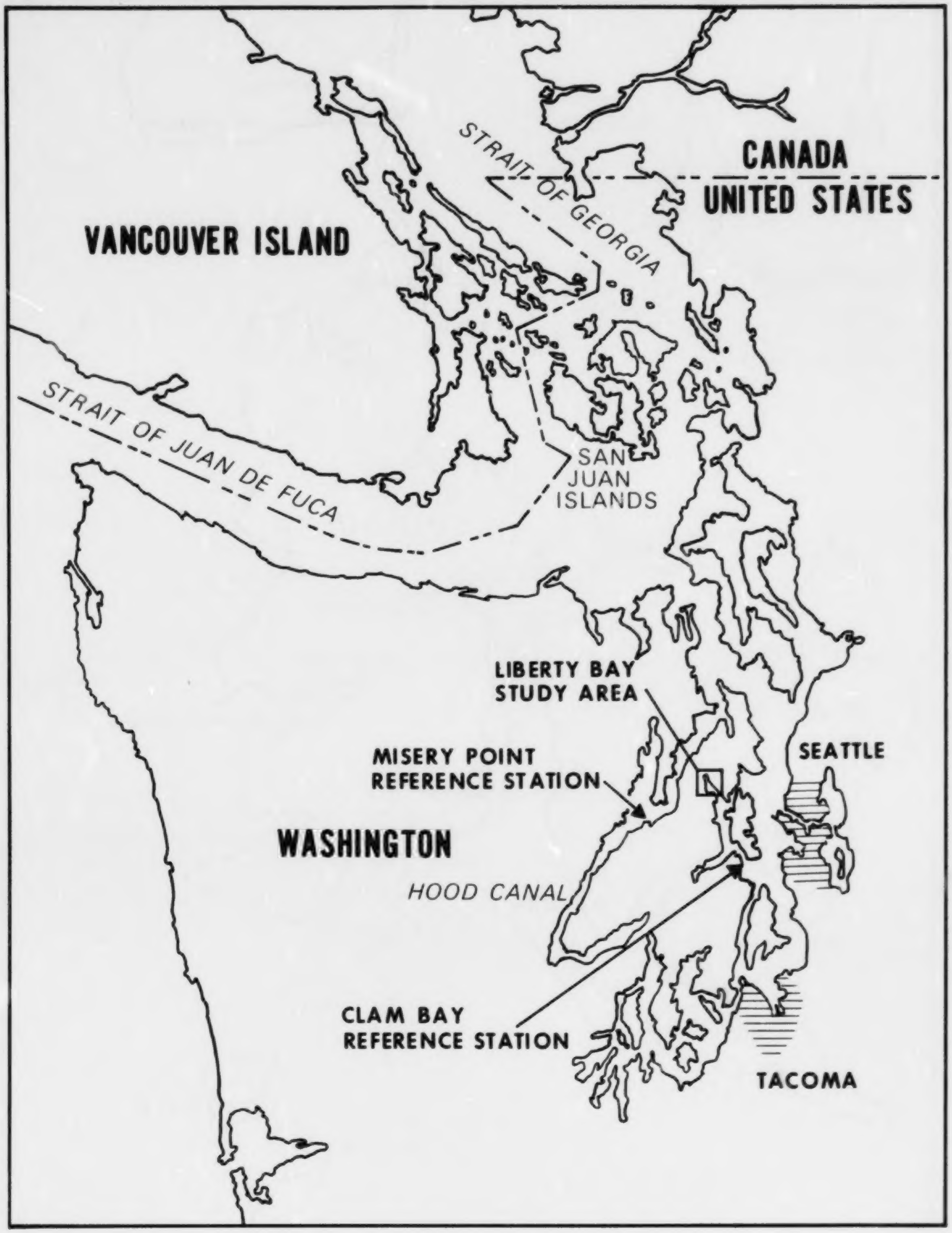
DESCRIPTION OF STUDY AREA

Location and General Use

Liberty Bay is one of several small bays comprising the west-central Puget Sound basin (Fig. 1). Although houses dot much of the Bay's shoreline, the major population centers bordering the Bay include Poulsbo in the northeast and the Navy's Keyport Torpedo Station in the southwest (Fig. 2). Marine waters in the area are used primarily for navigation, aesthetic enjoyment, recreation, shellfish culture, and the dilution of wastes.

Hydrography and Circulation

The Bay is part of the relatively shallow Port Orchard oceanographic system (Fig. 2) located west of Bainbridge Island and joined to the main Puget Sound basin by Agate Passage and Port Madison to the north and by Rich Passage to the southeast. Water depths and basin configuration determine the water circulation characteristics within the system. Although circulation is primarily tide-driven, it can be markedly influenced by wind in some locations. A narrow "S"-shaped channel formed by the Keyport and Lemolo peninsulas joins Liberty Bay with the north Port Orchard basin. The maximum depth of this channel is about 40 feet. Although the Bay proper has a small central basin with a maximum depth of 52 feet, depths throughout much of the northern and western portions of the bay are 15 feet or less, with mud flats being exposed during low tide (Lincoln and Collias, 1975).


CANADA
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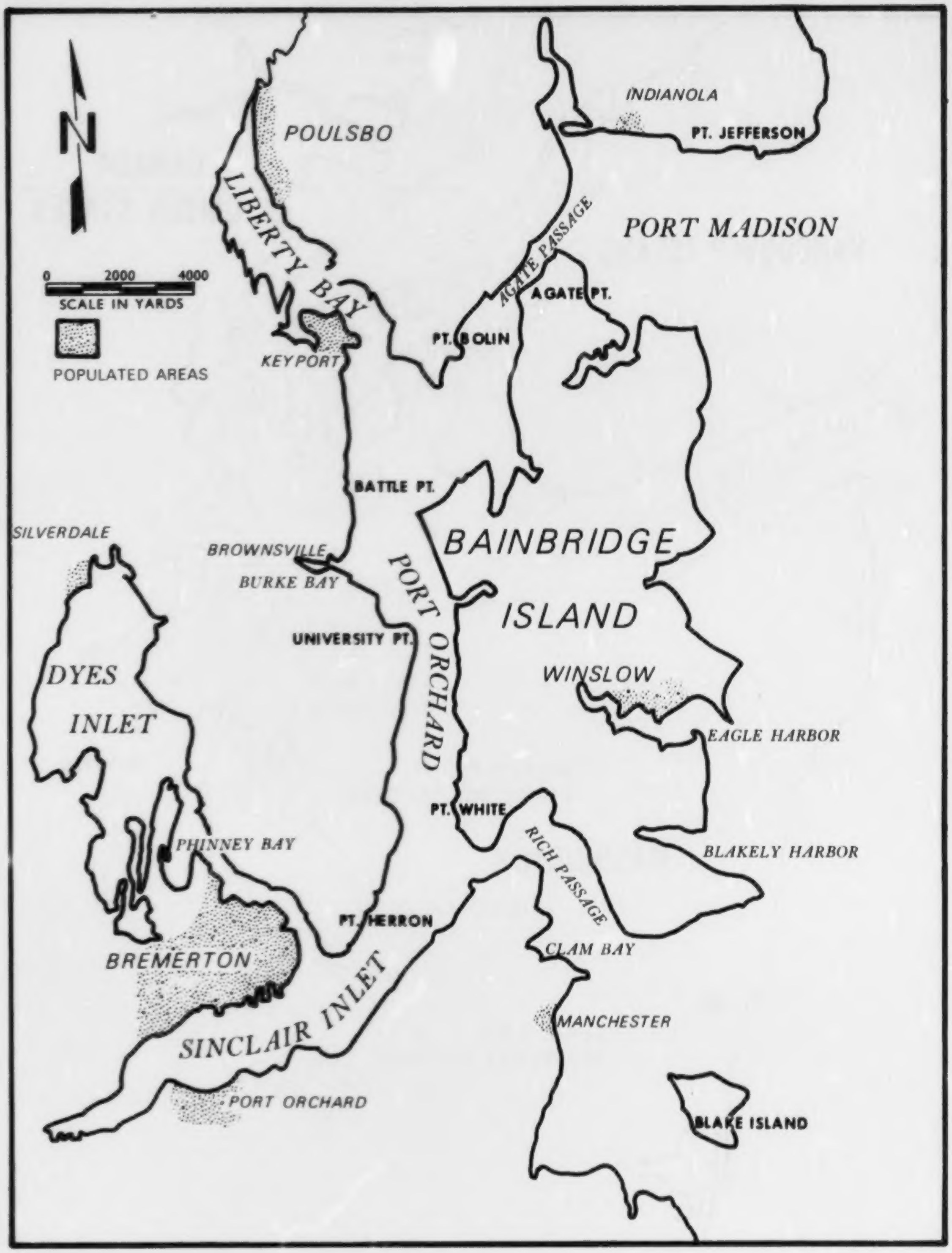
VANCOUVER ISLAND
STRAIT OF JUAN DE FUCA
SAN JUAN ISLANDS
LIBERTY BAY STUDY AREA
MISERY POINT REFERENCE STATION
SEATTLE
WASHINGTON
HOOD CANAL
CLAM BAY REFERENCE STATION
TACOMA

Figure 1. Location of Liberty Bay and survey reference stations.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SCALE IN YARDS
POPULATED AREAS
POULSBO
INDIANOLA
PT. JEFFERSON
PORT MADISON
LIBERTY BAY
AGATE PASSAGE
AGATE PT.
PT. BOLIN
KEYPORT
BATTLE PT.
SILVERDALE
BROWNSVILLE
BURKE BAY
UNIVERSITY PT.
PORT ORCHARD
BAINBRIDGE ISLAND
DYES INLET
WINSLOW
EAGLE HARBOR
PT. WHITE
RICH PASSAGE
BLAKELY HARBOR
PHINNEY BAY
PT. HERRON
CLAM BAY
BREMERTON
MANCHESTER
SINCLAIR INLET
PORT ORCHARD
BLAKE ISLAND

Figure 2. Port Orchard oceanographic system.

Most of the water involved in the flushing of Liberty Bay enters and leaves via Agate Passage (U.S. Dept. of Commerce, Tidal Current Charts; Lincoln and Collias, 1975). During drogue studies conducted by Roats Engineering (1970), water leaving Liberty Bay under conditions of maximum ebb tide reached a point just southwest of Point Bolin, then reversed direction after traveling a short distance to the northwest as flood tide began (Fig. 3). Water entering the Bay under maximum flood tide conditions tended to flow slightly east of the long axis of the Bay, reversing direction in a counterclockwise fashion off Poulsbo prior to ebb tide.

Sediments

Sediments within Liberty Bay show a distinct increase in their mud[a] content as the head of the Bay is approached (Fig. 4). Sediments in the narrow channel connecting Liberty Bay with the north Port Orchard basin have the lowest mud content (5-10%), while sediments in the deep basin north of Virginia Point and adjacent to Poulsbo exhibit the highest percentage mud (80-90%) (Harmon, Serwold, and Marine Science Technicians, 1976). These sediment characteristics appear to be strongly influenced by tidal velocities and current patterns, and are considered to be a major factor influencing the distribution of metals in surface sediments within the Liberty Bay system.

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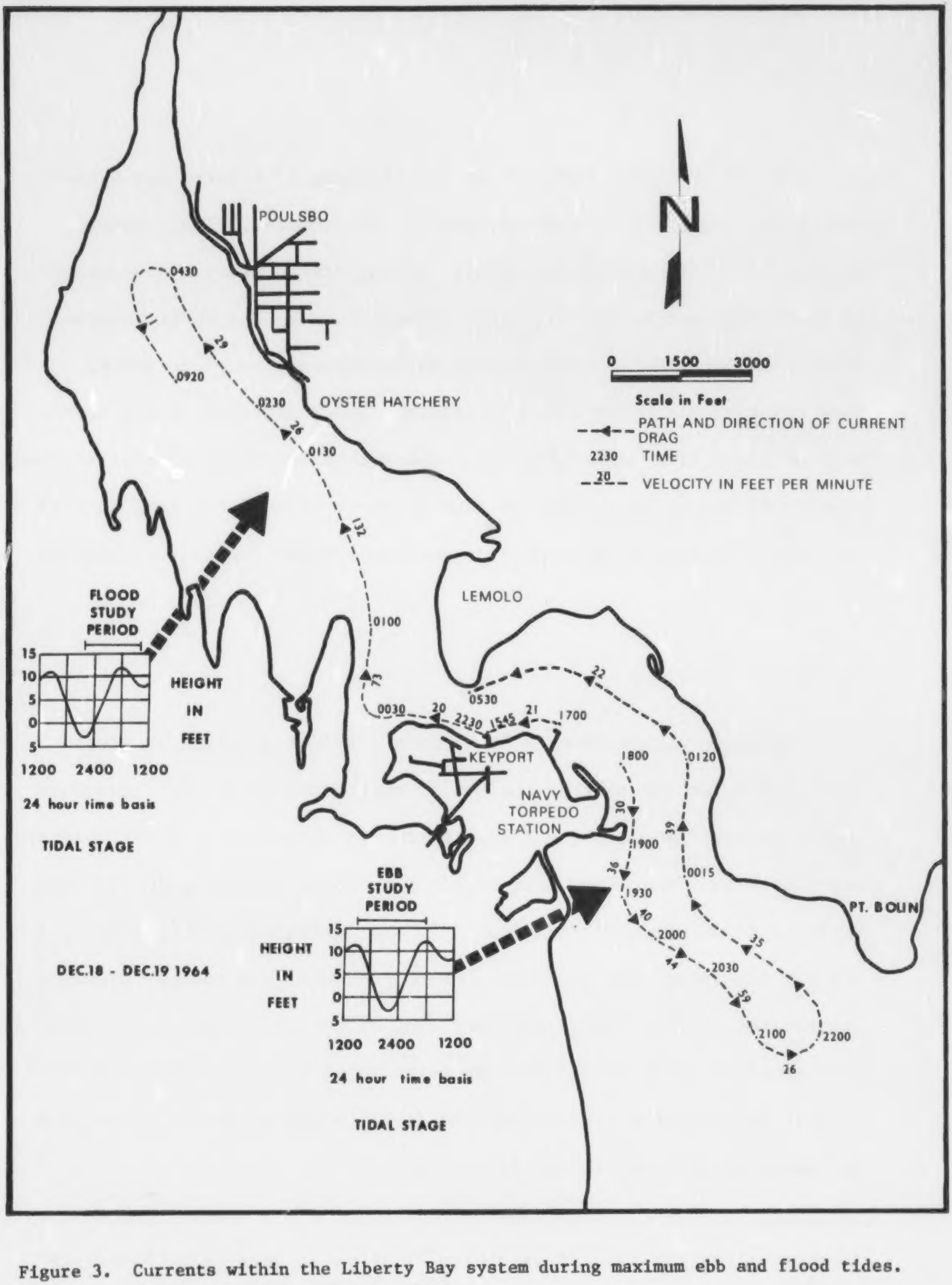
[a] General classification of particles <1/16 mm in size using Wentworth scale.


POULSBO
OYSTER HATCHERY
LEMOLO
KEYPORT
NAVY TORPEDO STATION
PT. BOLIN
N
0 1500 3000
Scale in Feet
PATH AND DIRECTION OF CURRENT DRAG
2230 TIME
20 VELOCITY IN FEET PER MINUTE
FLOOD STUDY PERIOD
EBB STUDY PERIOD
HEIGHT IN FEET
15 10 5 0 5
1200 2400 1200
24 hour time basis
TIDAL STAGE
DEC.18 - DEC.19 1964
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11
0920
29
0230
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132
0100
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39
36
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0015
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26

Figure 3. Currents within the Liberty Bay system during maximum ebb and flood tides. (After Roats Engineering, 1970)

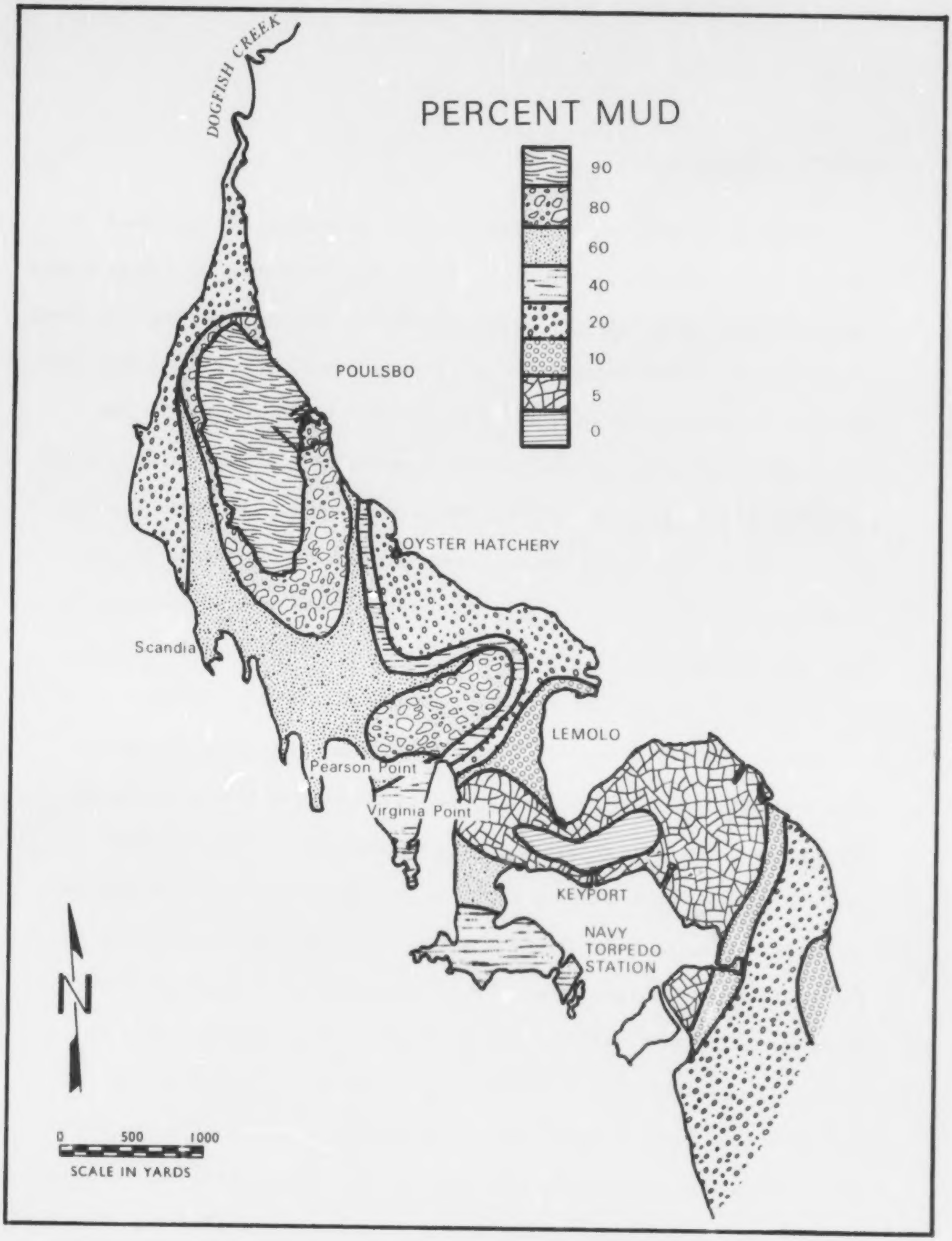
DOGFISH CREEK
PERCENT MUD
90
80
60
40
20
10
5
0
POULSBO
OYSTER HATCHERY
Scandia
LEMOLO
Pearson Point
Virginia Point
KEYPORT
NAVY
TORPEDO
STATION
N
0
500
1000
SCALE IN YARDS

Figure 4. Surface sediment characteristics within the Liberty Bay system. (After Harmon et al., 1976)

Fisheries Resources

Liberty Bay and Dogfish Creek support a variety of organisms of ecologic and economic importance. Adult chinook, coho, and chum salmon (Oncorhynchus tshawytscha, O. kisutch, and O. keta) enter Dogfish Creek to spawn, while the Bay provides a temporary habitat for juvenile coho and chum salmon migrating from other streams in Puget Sound. The Bay's intertidal beaches are important spawning grounds for surf smelt, Hypomesus pretiosus. In addition to supporting populations of young smelt, Liberty Bay serves as a nursery ground for important forage fishes such as herring, Clupea pallasii, and the Pacific sand lance, Ammodytes hexapterus (Personal Communication, Earl Finn, Washington State Dept. of Fisheries; Millikan, Penttila, and Day, 1974).

Large numbers of native littleneck clams, Venerupis staminea, Japanese littleneck clams, V. japonica, and butter clams, Saxidomus giganteus, inhabit many of the Bay's sand-gravel-cobble beaches. Of major economic importance to the area is the commercial cultivation of Pacific oysters. The average value of Pacific oysters landed in the vicinity of Poulsbo from 1972-1974 was $113,576 (Kitsap County Planning Department, 1973). Two sections of the Bay have been specifically classified as "conditionally approved" for the commercial harvesting of oysters and clams. The approved status of these areas is contingent on the proper operation of the sewage treatment plants discharging to the Liberty Bay system (Personal Communication, Max Hays, Washington State Department Social and Health Services).

Water Characteristics

Liberty Bay waters are classified as AA (Extraordinary) by the Washington State Department of Ecology. The DOE standards on which this classification is based appear in Appendix A.

Complete water quality data on Liberty Bay are limited. The information presented below is based on a recent oceanographic study of the Port Orchard system conducted during the spring and summer of 1975 by Lincoln and Collias (1975). The study was initiated to provide information for use in selecting marine sites for the future discharge of treated wastes from the Kitsap peninsula.

Temperature -

Spring water temperatures in Liberty Bay generally ranged from 9 C to 10 C throughout the water column, with temperatures increasing slightly toward the head of the Bay. By early August surface temperatures were as high as 17 C in certain locations, and a vertical temperature gradient had become established in the lower Bay.

Liberty Bay waters were generally 2 C warmer than other waters of the Port Orchard system. This characteristic was attributed to the warming effect of the mud flats at the head of the Bay coupled, of course, with the overall influence of solar radiation.

Salinity -

Salinities throughout Liberty Bay generally ranged from 28 - 29.5 o/oo, with the greatest dilution confined to the head of the Bay where Dogfish Creek enters the system.

Nutrients -

Waters entering Liberty Bay from Port Orchard contained sufficient quantities of inorganic phosphate, silicate, and nitrate to support a substantial spring bloom of phytoplankton. Nutrient reductions associated with increases in phytoplankton production suggested that silicate and nitrate were the limiting nutrients in the Port Orchard system.

The productivity of waters at a representative station off Battle Point (Fig. 2) ranged from a low of about 10 mg-C/m^3/0.5 day in April to a high of 742 mg-C/m^3/0.5 day measured during the phytoplankton bloom in May. Companion chlorophyll-a values ranged from an April low of <2 mg/m^3 to a May high of 20 mg/m^3 in the upper 6 meters.

Dissolved Oxygen -

Dissolved oxygen concentrations in Liberty Bay usually ranged from about 7.5 - 9.5 mg/l throughout the water column and were never observed to be less than 6.9 mg/l. In the spring, concentrations as high as 14 mg/l (160% saturation) were measured in the surface waters of the upper Bay. These elevated concentrations resulted from increased primary production associated with the spring phytoplankton bloom.

Point Source Discharges

The sewage treatment facility of the City of Poulsbo constitutes the major point source discharge to the Bay. This primary treatment plant, constructed in 1942, serves a population of about 2000 persons and has an average discharge of 0.25 million gallons per day (MGD) (State of Washington, 1974). Treated wastes are discharged south of the Poulsbo marina breakwater at a depth of -12 ft (MLLW) (Fig. 5) (Personal communication, Herb Armstrong, City Engineer, Poulsbo, WA). The Poulsbo plant has not yet been issued an NPDES permit. Planning for the construction of larger and more effective treatment facilities was initiated by the City a number of years ago. Decisions concerning these plans are pending.

Major point source discharges to waters adjacent to Liberty Bay include the waste treatment facilities of the City of Keyport (NPDES Permit WA-002445-7) and the Navy Keyport Torpedo Station (NPDES Permit WA-002198-9). These facilities are located along the northern shore of the Keyport peninsula and discharge treated wastes at depth into the channel connecting Liberty Bay with the north Port Orchard basin (Fig. 5). Keyport's extended aeration plant was constructed in 1968 and has an average discharge of 0.055 MGD.

The Torpedo Station operates an activated sludge sewage treatment plant having an average discharge of 0.088 MGD in 1975. In addition to handling sanitary wastes, this facility presently receives pretreated discharges from the Station's electroplating plant. The plating plant operates on an 8 hour day with a discharge of 0.014 MGD or less. From about 1936 to February 24, 1975, however, all metallic electroplating wastes were discharged without treatment at or near the surface of the channel near Liberty Bay. The discharge site was located southeast of the present Navy STP outfall (Fig. 5). After this date, when flows of untreated electroplating wastes occasionally exceeded the approximate

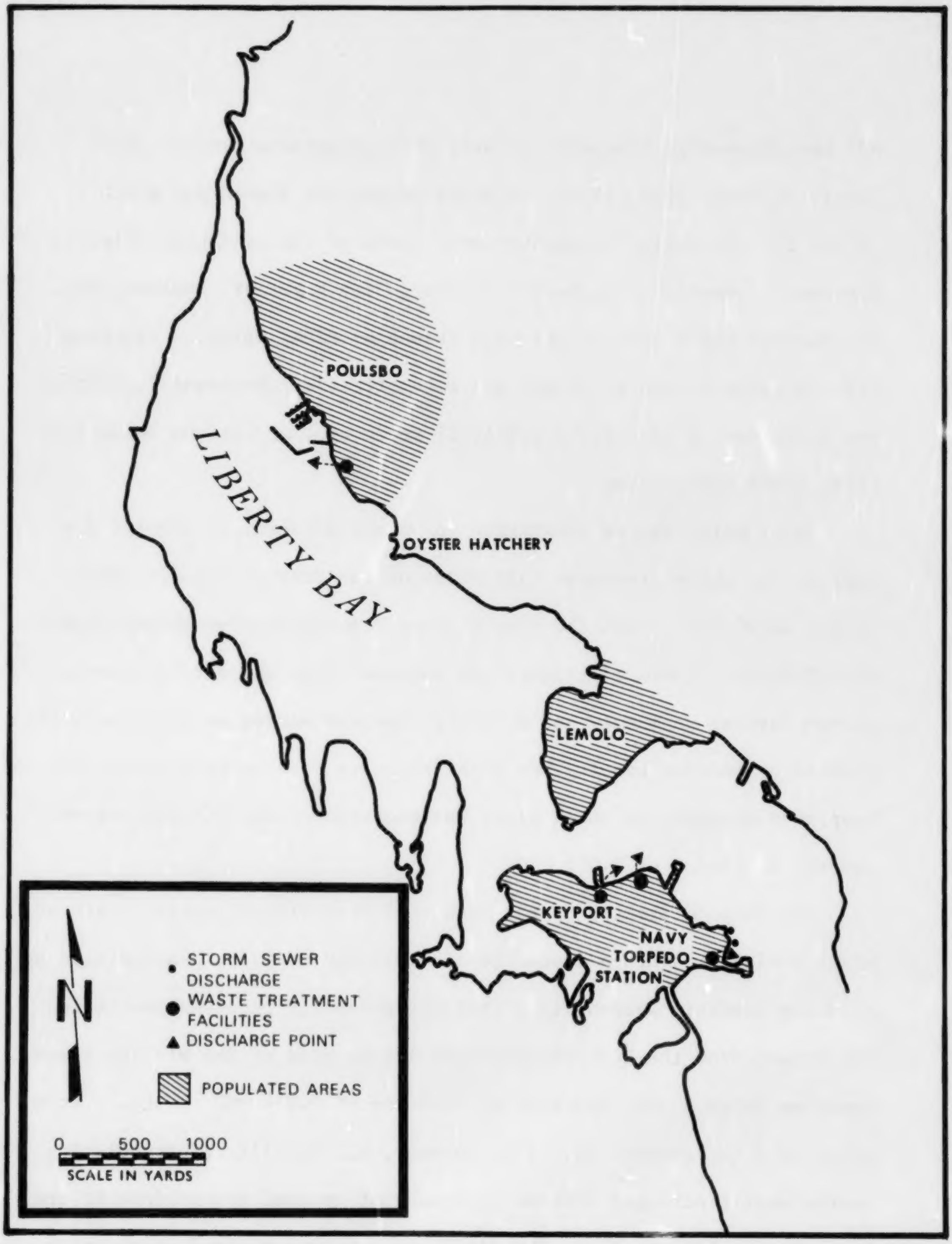
POULSBO
LIBERTY BAY
OYSTER HATCHERY
LEMOLO
KEYPORT
NAVY TORPEDO STATION
STORM SEWER DISCHARGE
WASTE TREATMENT FACILITIES
DISCHARGE POINT
POPULATED AREAS
0
500
1000
SCALE IN YARDS
N

Figure 5. Location of waste treatment facilities and major discharge points within the Liberty Bay system.

30 gallon per minute (GPM) capacity of the pretreatment facility, or when the STP was not operating properly, the excess untreated plating wastes were discharged to the channel southeast of Liberty Bay through the original outfall (Personal Communication, Dick Boughner, U.S. Navy, Seattle, WA). Such discharges were not permitted under the National Pollutant Discharge Elimination System (NPDES) permit applying to the Torpedo Station STP. This situation has since been corrected resulting in the overflow outfall being sealed shut in November, 1975.

The volume and nature of the plating wastes have remained about the same over the last few years. The discharge capacity of the plating plant will be increased, however, when improvements currently being made in the pretreatment facilities are completed later this year (Personal Communication, Dick Boughner, U.S. Navy, Seattle, WA).

Minor point source discharges to the Liberty Bay system include oyster washings from Coast Oyster Company (NPDES Permit WA-000116-3) as well as the drainage from numerous storm sewer outfalls. In addition to these sources, the discharge of heated seawater from the Sea Farms oyster hatchery constituted an unpermitted thermal discharge to the upper Bay before the hatchery discontinued its operation.

Nonpoint Source Discharges and Other Activities

A small landfill located in the southwestern sector of the Navy Torpedo Station constituted a potential nonpoint source discharge to the Liberty Bay system. Limited quantities of assorted refuse were discarded at the site until it was closed in 1975. Reports that mercury-cadmium batteries had in the past been disposed of in the vicinity of the landfill could not be confirmed (Personal Communication, Dick Boughner, U.S. Navy, Sand Point, WA).

Another activity of potential significance that was considered during the survey included past experimental applications of various toxicants to small areas of Liberty Bay for the control of Japanese oyster drills, *Ocinebra japonica*. Field evaluations of such agents as mercuric chloride, copper sulfate, cuprous chloride, cupric chloride, and lead nitrate were conducted during the late 1940's and early 1950's, with orthodichlorobenzene and Sevin being applied on a small scale in 1960 (Bajkov, 1949; Fullington and Woelke, 1951-1953; Lindsay, 1961).

The grouting of several sewer lines serving the Poulsbo STP was also considered. Grouting activities were only conducted, however, between August 1, 1975 and October 12, 1975. The grout used was an acrylamide gel (Cyanamid AM-9) that did not contain mercury (Personal Communication, Gel-Co Grouting Surface, Salem, OR, and American Cyanamid Co., Wayne, NJ).

METHODS

Field Activities

Sampling -

Sampling of Liberty Bay and reference stations established in Hood Canal (Misery Point) and Clam Bay (Manchester) (Figs. 1 and 6) was conducted September 12 - 19, 1975. Water, sediment, fish and shellfish samples were collected during this period. Additional water samples were collected in October, November and December, 1975 to continue to provide water quality surveillance as well as to help answer questions raised about the goodness of the analytical techniques being used.

Specific details concerning the collection and storage of each type of sample are presented below.

Water

Water samples were collected with a polyvinyl chloride (PVC) Van Dorn bottle or Kemmerer sampler, then poured into 1-liter, polyethylene Cubitainers for chemical analysis or into clean, 4-liter polypropylene jugs for bioassay. On occasion, surface samples were collected directly in the Cubitainers or polypropylene jugs. Samples collected for chemical analysis were stabilized in accordance with the EPA Manual of Methods for Chemical Analysis of Water and Wastes (1974) depending on the chemical parameter of interest. All water samples were placed in ice chests for transport to the laboratory. Chemical analysis of the samples was initiated immediately, or as

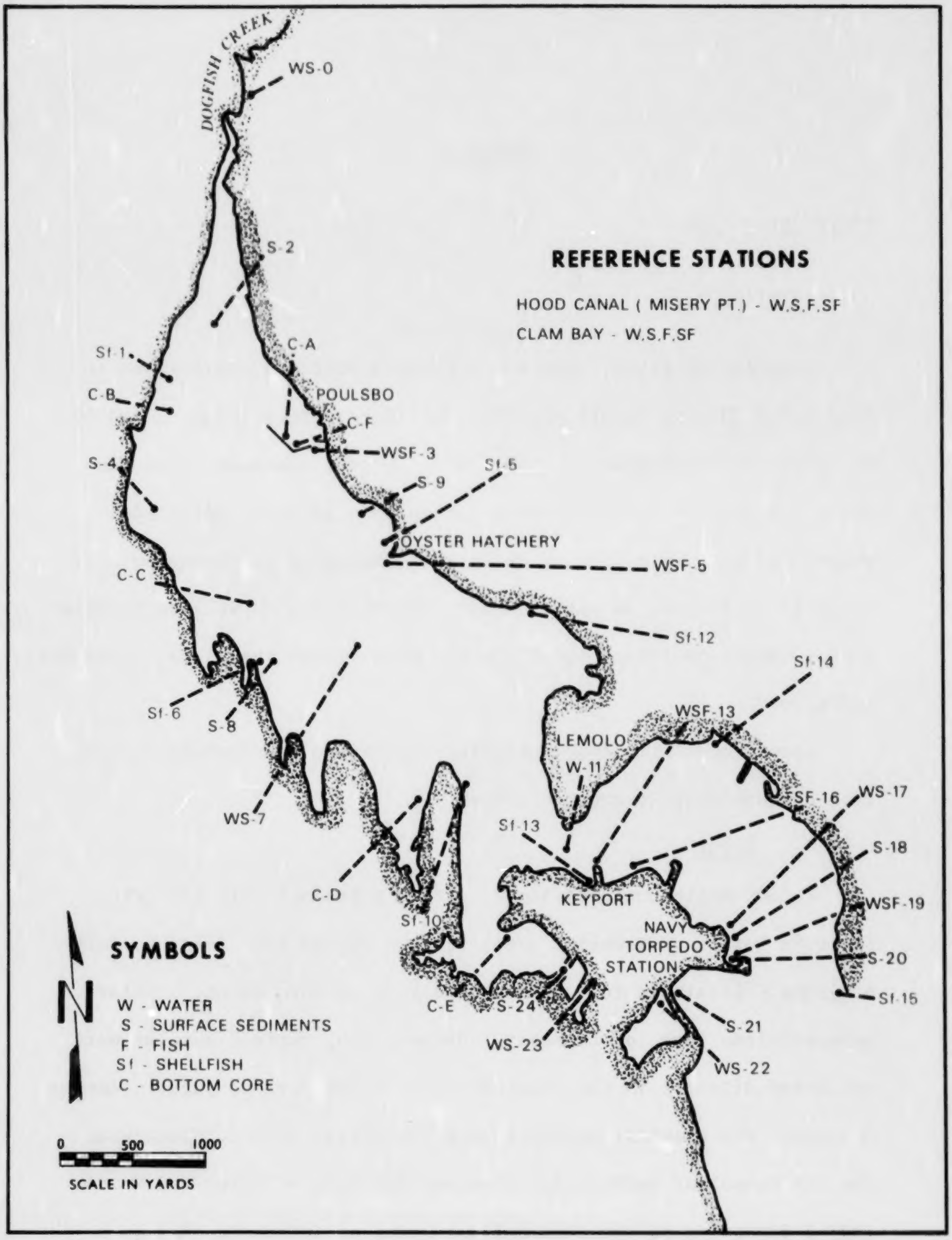
DOGFISH CREEK
WS-0
S-2
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) - W,S,F,SF
CLAM BAY - W,S,F,SF
C-A
Sf-1
C-B
POULSBO
C-F
WSF-3
S-4
S-9
Sf-5
OYSTER HATCHERY
WSF-5
C-C
Sf-12
Sf-14
Sf-6
S-8
WSF-13
LEMOLO
W-11
WS-7
SF-16
WS-17
Sf-13
S-18
C-D
KEYPORT
WSF-19
Sf-10
NAVY TORPEDO STATION
S-20
Sf-15
SYMBOLS
N
W - WATER
S - SURFACE SEDIMENTS
F - FISH
Sf - SHELLFISH
C - BOTTOM CORE
C-E
S-24
S-21
WS-23
WS-22
0
500
1000
SCALE IN YARDS

Figure 6. Location of sampling stations.

soon as possible, upon their receipt by the laboratory. Bioassay samples were refrigerated at 1 C for approximately 24 hours before being prepared for toxicity assessment. One 4-liter sample of Clam Bay water was collected the morning of September 15 and carried along during the sampling tour. This sample served as the "carry along control" to detect changes in water quality associated with the collection, transport, and storage of the bioassay samples.

During the period of most intensive sampling (September 15), water samples were collected from five Liberty Bay stations at the surface, mid-depth, and bottom during low slack and high slack tides. Samples collected from Hood Canal and Clam Bay (September 17) were collected only at the surface and bottom under conditions of low and high tide respectively. All other water samples could be characterized as surface grabs collected only for chemical analysis under a variety of tidal conditions.

Sediment

Surface sediments were collected with a Van Veen grab or by hand at eighteen Liberty Bay stations (Fig. 6) and at the two reference stations. Sediment was transferred to, or was collected in, new glass jars and stored at about 4 C until analyzed or bioassayed.

Duplicate sediment core samples were collected from each of six Liberty Bay stations (Fig. 6) with a Phleger corer equipped with new plastic core liners. The cores were refrigerated immediately after being collected. Later, they were frozen in their liners to facilitate the removal of top and middle sections for chemical analysis.

The bottom portion of each core was retained by the corer bit. These sections were placed in glass jars and analyzed as soon as possible after collection.

Fish

Bottom fishes were collected with a spear gun by SCUBA divers from five subtidal stations in Liberty Bay and from the two survey reference stations (Fig. 6). The fishes were later frozen in plastic bags. Prior to chemical analysis the samples were thawed, measured, and filleted. The muscle tissue fillets from each fish were placed in glass jars and kept refrigerated (4 C) until analyzed.

Shellfish

Several species of shellfish were collected by hand during low tide at ten intertidal stations in Liberty Bay (Fig. 6) as well as from the Hood Canal and Clam Bay reference stations. Samples of oysters, butter clams, and littleneck clams, each consisting of about six, twelve, and twenty-four specimens respectively, were placed in plastic bags and frozen in the shell before being shucked. Drained shellfish meats were stored in glass jars at 4 C.

Hydrographic Measurements -

During periods of intensive water sampling, several hydrographic parameters were measured *in situ* at each sampling site by the use of a portable water quality monitor (Hydrolab Surveyor 6-D). These parameters included water temperature, dissolved oxygen, pH, and depth. The instrument was calibrated prior to each sampling tour.

Laboratory Activities

Chemical -

The need for descriptive information on the chemical character of Liberty Bay required that a variety of chemical and physical parameters be measured in the water, sediment, and biological samples collected during the survey. These measurements were performed according to the methods listed in Table 1.

The accuracy (recovery efficiency) of major chemical analyses performed on samples collected during the survey was determined by the standard additions technique (U.S. EPA, APTD-1132, 1973). Standard reference samples used for this purpose were obtained from the EPA Environmental Monitoring and Support Laboratory, Cincinnati, Ohio.

Biological -

Oyster Embryo Bioassay

Selected seawater, sediment, and sewage treatment plant (STP) effluent samples were assayed September 16 using modifications of the general Pacific oyster embryo assay technique of Woelke (1972). The actual procedures followed during each step of the assay are described below.

Sample Preparation

(Water) 1000-ml volumes of sample were poured into each of two 1-liter polyethylene beakers.

Table 1. Analytical Methods Followed During Survey of Liberty Bay.

Parameter	Sample Type	Analytical Method Reference
Metals (Total)		
Sb, As, Cd, Cr, Cu, Fe, Pb, Mn, Ni, Se, Zn	FW	U.S. EPA - Methods for Chemical Analysis, 1974.
	SW	Lakanen, 1966. Perkin-Elmer Instrument Manual, 1973; U. S. EPA, Methods for Chemical Analysis, 1974.
	Sd Sh	Perkin-Elmer Instrument Manual, 1973; U. S. EPA - Methods for Chemical Analysis, 1974, Lakanen, 1966.
Hg	FW, SW, Sd, Sh	U. S. EPA Methods for Chemical Analysis, 1974.
Cr (Hexavalent)	FW, SW	APHA - Standard Methods, 1972.
Organochlorine Compounds	Sd, Sh	U. S. EPA - Analysis of Pesticide Residues, 1974.
Nutrients		
Total Phosphorus; NH_3-N	FW, SW	U. S. EPA - Methods for Chemical Analysis, 1974.
Miscellaneous		
TOC; BOD; MBAS; Cyanide; Turbidity; N-Kjeldahl; Total Volatile Solids; Total Solids	FW, SW Sd	U. S. EPA - Methods for Chemical Analysis, 1974.
Total Sulfide	FW, SW, Sd	APHA - Standard Methods, 1972.
PBI (Pearl-Benson Index)	FW, SW	Barnes, C.A. *et al.*, 1963.
Salinity	SW	Zerbe and Taylor, 1953.

FW	Freshwater
SW	Seawater
Sd	Sediment
Sh	Fish and Shellfish

Ten 1-liter volumes of Clam Bay seawater collected during the sample preparation activities served as the "bioassay control."

(Sediment) 10, 1, 0.1, and 0.01 grams of sediment were weighed separately into each of two 1-liter polyethylene beakers. The contents of the beakers were then brought up to 1000 ml with Clam Bay, bioassay control, seawater.

(STP Effluent) Serial dilutions of treated effluent were made based on a dilution factor of 2.0. Each dilution was prepared by adding appropriate volumes of effluent to each of two 1-liter polyethylene beakers, then bringing the contents up to 1000 ml with Clam Bay, bioassay control, seawater. Care was taken to maintain the salinity of the final effluent preparations above 24 o/oo. Salinities <20 o/oo have been found to adversely affect oyster embryo development (Woelke, 1972).

Oyster Spawning and Sample Inoculation

Spawning was induced in adult Pacific oysters harvested from Burley Lagoon (Western Oyster Co.) and conditioned at approximately 19 C for three weeks. Eggs were fertilized with a sperm suspension obtained by spawning, and each 1-liter sample preparation was inoculated with 3.0×10^4 developing embryos approximately two hours after fertilization. The cultures were covered with brown paper and air-incubated for 48 hours at 20 C.

Salinity and pH measurements were made on selected sample preparations at the end of the 48-hour incubation period.

Termination

Sediment assays were terminated by carefully vacuuming the larval culture into a flask without disturbing the settled sediment. The culture was then mixed with a magnetic stirrer and 10 milliliters transferred to a screw-cap vial and preserved in 5% formalin. All other assays were terminated as described above, but without the initial vacuum transfer step. This procedure was used to prevent the mechanical loss of larvae using the filter termination technique as shown to be possible by Cardwell *et al*., (In preparation).

Larval Enumeration

The fluid overlying the preserved larvae was removed with suction and the larvae quantitatively transferred to a Sedgwick-Rafter cell. The normal and abnormal larvae were counted under a microscope at 100 X. Those embryos failing to develop to fully-shelled, straight hinge larvae were considered to be abnormal.

Bioassay Evaluation

Evaluation of oyster embryo response to the various sample preparations was based on larval development and survival using measurements of per cent larval abnormality and per cent relative larval survival.

> *Per Cent Larval Abnormality*: The proportion of abnormal larvae to the total number of larvae (normal and abnormal) in a sample.
>
> *Per Cent Relative Larval Survival*: The proportion of the total number of larvae (normal and abnormal) in a sample to the mean total number of larvae (normal and abnormal) in the "bioassay control" sample.

Plankton Identification and Enumeration

The major phytoplanktonic and protozoan species present in selected water samples from Liberty Bay were identified by personnel of EPA's Narragansett Environmental Research Laboratory, Narragansett, Rhode Island.

Phytoplankton population densities were determined by the use of a hemacytometer.

Compliance Monitoring Inspection

An independent compliance monitoring inspection of the Navy Torpedo Station STP was conducted by EPA in conjunction with the chemical and biological survey of Liberty Bay. The primary purpose of the inspection was to assess compliance with the National Pollution Discharge Elimination System (NPDES) permit conditions. This activity, coupled with effluent sampling of the Poulsbo and Keyport STPs, also provided needed information on the characteristics of the major point source discharges to the Bay. The field and laboratory methods that were applied were generally the same as those described earlier.

RESULTS AND DISCUSSION

Chemical and Physical Characteristics

Water -

General Conditions

The basic chemical and physical properties of selected Liberty Bay, Clam Bay and Hood Canal waters during the period September 15 - October 10, 1976 are presented in Table 2.

Liberty Bay water temperatures generally decreased with depth and toward Dogfish Creek. Bottom water temperatures ranged from 13.5 - 16.0 C, while surface waters in the central and lower Liberty Bay system ranged from 16.0 - 17.0 C. Salinity and pH values showed little variation, ranging from 29.4 - 30.4 o/oo and 7.2 to 8.0, respectively. Turbidities usually ranged from 0.8 - 7.5 nephelometric turbidity units (NTU), with a high value of 27 NTU characterizing the bottom water at Station WSF-5 (Sea Farms hatchery site).

Dissolved oxygen concentrations (DO) in the Bay's surface waters ranged from 9.1 - 12.5 mg/1, while the overall range of DO levels in waters collected at middepth and near the bottom ranged from 4.8 - 8.5 mg/1. Similarly, surface total organic carbon (TOC) values ranged from 2.0 mg/1 to as high as 50 mg/1, with middepth and bottom values ranging from 2.0 - 3.0 mg/1. The higher pH, DO, and TOC characteristics of the surface waters undoubtedly reflected the influence of increased phytoplankton growth in the Bay's surface waters. A phytoplankton bloom observed in east-central Liberty Bay on September 15 was evidence of

Table 2. General Physical and Chemical Properties of Liberty Bay, Clam Bay, and Hood Canal Waters.

Station	Date	Time	Tidal Stage	Depth (m)	Temperature (C)	Salinity °/oo	pH	Turbidity NTU[a]	Dissolved Oxygen (mg/1)	PBI[b] (mg/1)	N-NH3 (mg/1)	Total Phosphorus (mg/1)	Total Organic Carbon (mg/1)	Sulfide (µg/1)	Cyanide (mg/1)	MBAS (mg/1)
Liberty Bay Stations																
WS-0 (Dogfish Creek)	10-7-75	1215	Low-Ebb	0	10.1			1.3		5.0	0.02					0.043
WSF-3 (Near Poulsbo STP Outfall)	9-15-75	1630	High-Slack	0	14.9	30.4	8.0	2.6	12.5	<1.0	0.03	0.28	16.0	<0.02		0.100
				5	14.0	29.5	7.6	1.5	8.5	2.0	0.05		3.0	<0.02	0.01	0.045
				9	13.5	29.7	7.2	1.8	4.8	<1.0	0.07		3.0	<0.02		0.045
WSF-3	9-15-75	1055	Low-Flood	0	14.0	29.5	7.7	1.6	9.1	2.0	0.12	0.20	9.0	<0.02		0.055
				3	13.8	29.4	7.4	1.4	7.0	3.0	0.04		2.0	<0.02	<0.01	0.030
				6	13.5	29.7	7.5	4.1	6.5	<1.0	0.03		3.0	<0.02		0.023
WSF-5 (Oyster Hatchery Site)	9-15-75	1610	High-Slack	0	15.0	29.5	7.8	2.8	12.0	1.0	0.03	0.22	17.0	<0.02		0.080
				5	14.6	29.5	7.6	1.2	8.3	1.0	0.04		2.0	<0.02	<0.01	0.013
				9	14.0	29.7	7.5	27	7.8	9.0	0.06		2.0	<0.02		0.020
WSF-5	9-15-75	1015	Low-Flood	0	14.5	29.6	7.7	1.2	10.0	3.0	0.04	0.10	4.0	<0.02		0.090
				3	14.0	29.7	7.5	1.2	7.8	1.0	0.03		3.0	<0.02	<0.01	0.018
				6	14.0	29.7	7.5	2.8	7.3	<1.0	0.04		3.0	<0.02		0.010
WS-7 (Mid-Bay)	9-15-75	0940	Low-Flood	0	17.0	29.4	7.7	7.5	10.5	3.0	0.07	0.55	50.0	<0.02		0.440
				3	13.5	29.7	7.5	1.7	7.2	3.0	0.04	0.09	3.0	<0.02	<0.01	0.013
				6	13.5	29.9	7.5	2.4	6.8	1.0	0.05	0.10	3.0	<0.02		0.013
W-11 (Mouth of Bay)	9-15-75	1545	High-Slack	0	16.0	29.7	7.7	1.2	11.0	1.0	0.02	0.11	4.0	<0.02		0.055
				6	15.0	29.8	7.6	1.3	8.0	1.0	0.03		2.0	<0.02	<0.01	0.020
				12	13.5	29.9	7.5	1.0	7.1	3.0	0.04		2.0	<0.02		0.013
W-11	9-15-75	0900	Low-Slack	0	16.5	29.8	7.7	0.9	10.0	1.0	0.02	0.08	2.0	<0.02		0.045
				5	16.5	29.5	7.7	1.2	8.1	1.0	0.04		3.0	<0.02	<0.01	0.015
				9	16.0	29.5	7.6	2.3	7.1	2.0	0.04		3.0	<0.02		0.010
WSF-13 (Keyport STP Outfall)	9-15-75	0800	Low-Slack	0	17.0	29.8	7.7	1.1	11.9	<1.0	0.03	0.82	3.0	<0.02		0.045
				6	17.0	29.8	7.7	1.0	7.8	<1.0	0.03		3.0	<0.02	<0.01	0.020
				12	14.7	29.9	7.6	0.8	7.2	1.0	0.03		3.0	<0.02		0.010
WS-17 (NTS[b] Paint Shop Storm Sewer Outfall)	9-17-75	1230	Low-Flood	0												
WSF-19 (Near NTS Plating Plant Overflow)	9-17-75	1200	Low-Flood	1							0.04		2.0		<0.01	
WS-22 (NTS S.E. Lagoon)	9-17-75	0900	Low-Ebb	0		5.8		3.9		5.0	0.05		9.0		<0.01	
WS-23 (NTS N.W. Lagoon)	10-10-75	1215	High-Ebb	0				2.7		<1.0	0.09					
Reference Stations																
Hood Canal (Misery Pt.)	9-16-75	1110	Low-Flood	0	15.6	24.2	7.9	0.5	11.8	2.0	0.02	0.032	3.0	<0.02	<0.01	
				8	11.5	29.3	7.5	1.6	7.7	2.0	0.02		3.0	<0.02		
Clam Bay	9-16-75	1355	Low-Flood	0	11.9	29.8	7.6	0.5	8.1	1.0	0.03	0.074	2.0	<0.02	<0.01	
				11	11.2	29.9	7.6	0.6	8.1	1.0	0.04		2.0	<0.02		

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[a] NTU Nephelometric turbidity units

[b] PBI Pearl-Benson Index

[c] NTS Navy Torpedo Station

[d] MBAS Methylene Blue Active Substances

such increased primary productivity. The species composition and possible significance of the bloom are discussed in more detail in the Biological section of this report.

Ammonia-nitrogen ($N-NH_3$) levels generally ranged from 0.02 - 0.07 mg/l, with the highest value of 0.12 mg/l being measured at the surface near the Poulsbo STP outfall during low tide. These values were similar to the levels measured in Liberty Bay by Lincoln and Collias (1975); however, the vertical and horizontal concentration gradient they observed earlier was not as apparent in September.

Total phosphorus concentrations in the Bay's surface waters (0.098 - 0.55 mg/l) were consistently higher than those at the surface of the channel leading from the Bay (0.080 - 0.082 mg/l). There appeared to be a direct relationship between these concentrations and TOC values throughout the system. This relationship probably reflected increases in the concentrations of cell-associated phosphorus linked to substantial increases in the standing crop of phytoplankton.

Sulfide levels measured throughout the water column were below detectable limits (<0.020 mg/l). The indeterminately low nature of these values precluded the assessment of their biological significance based on sulfide concentrations ($\geq$0.01 mg/l) suggested as hazardous by the National Academy of Sciences (1972). Both the indeterminate levels and the suggested hazardous concentrations were considerably lower, however, than the 0.2 mg/l sulfide levels reported by Sea Farms, Inc. in surface waters near the oyster hatchery April 28, 1975 (Personal Communication, Sea Farms, Inc. Poulsbo, WA). The only known activity that may have been responsible for the high sulfide concentrations reported by Sea Farms was a bottom dredging operation that was conducted just north of the Poulsbo marina from April 2-21, 1975 (Personal Communication, Herb Armstrong, Roats Engineering, Poulsbo, Washington). Dredged material removed from the Bay was used to backfill a shoreline bulkhead near the dredge site. Consequently, the settling and draining of this material may have had a limited effect on the Bay's water quality for some time following the completion of dredging. Although it was possible that the dredge and spoil disposal operation resulted in an increase in seawater - sulfide concentrations to harmful levels, no positive correlation between the total sulfide content of Liberty Bay sediments and acute oyster embryo response could be demonstrated in the laboratory (page 103).

The concentrations of Pearl-Benson Index (PBI)-sensitive substances[a] generally ranged from 1.0 - 3.0 mg/l; however, an unexplained high value of 9.0 mg/l characterized bottom waters at the Sea Farms hatchery site (Station WSF-5). The unusually high turbidity of this water (27 NTU) suggested that a small amount of bottom sediment may have been inadvertently collected along with the sample of bottom water. If a portion of this bottom material were PBI-sensitive, it could explain the 9.0 mg/l PBI measurement. Based on the reports of Gunter and McBee (1960) and Woelke (1960), the 9 mg/l PBI value approached or slightly exceeded the levels of sulfite waste liquor (as measured by the Pearl-Benson method) found to affect Pacific oyster development. No discharges of sulfite waste liquor are known to have been made to Liberty Bay. Therefore, the PBI-sensitive substances in the Bay probably consisted primarily of naturally occurring tannins and lignins. Although of possible biological significance, the effect of such substances on oyster embryo development and survival has not been well defined. The levels of PBI-sensitive substances measured in Liberty Bay waters did not, however, appear to adversely affect embryo response during the acute oyster embryo assays performed on these waters (page 91).

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[a] Substances responding positively to the Pearl-Benson method of estimating sulfite waste liquor concentrations in water.

Cyanide concentrations ranged from <0.01 mg/l to a determinate level of 0.01 mg/l at Station WSF-3 near the Poulsbo STP outfall. Although the 0.01 mg/l value equaled the hazardous level (≥0.01 mg/l) suggested by the National Academy of Sciences (1972), this measurement represented the lower limit of detectability and, therefore, should be confirmed before assessing its possible biological significance.

Concentrations of methylene blue active substances (MBAS) in Liberty Bay ranged from 0.10 - 0.440 mg/l, with distinctly higher levels being observed in surface waters. The measurement of MBAS is commonly used to indirectly determine the concentration of linear alkylate sulfonate (LAS) surfactants. These substances (LAS) are currently used in household detergents and are considered to be hazardous to freshwater organisms at concentrations exceeding 0.2 mg/l (National Academy of Sciences, 1972). Although the Poulsbo STP was shown to be a major contributor of MBAS to the Bay (Appendix B), the direct relationship between the MBAS and TOC levels measured in the Bay suggested that the elevated MBAS levels in the Bay resulted from the interference of chlorophyll and other pigments associated with the algal bloom observed during the survey. It was not possible, therefore, to assign any biological significance to these inflated MBAS values.

Metal Concentrations

Most of the total metal levels measured in Liberty Bay waters exceeded concentrations reported by the National Academy of Sciences (1972) as characterizing unpolluted seawater. Levels of cadmium, iron, mercury, nickel, and zinc even exceeded concentrations suggested by the Academy as being hazardous in the marine environment. Significantly, most of the metal levels measured at the survey reference stations in Clam Bay and Hood Canal also appeared to be elevated. In some cases these concentrations equaled or exceeded metal levels detected in Liberty Bay.

Before assessing the significance of possible hazardous heavy metal levels that appeared to be present in Liberty Bay, the extraordinarily high "background" concentrations of metals measured at the Clam Bay and Hood Canal reference stations had to be explained. Although the proximity of Clam Bay to industrialized areas of Puget Sound was considered to lend some credence to the high metal levels measured there, no such explanation could be offered in the case of Hood Canal. The need for such an explanation was underscored by the understanding that Clam Bay and Hood Canal supported healthy biological communities indicative of good water quality. Furthermore, there were no apparent geochemical explanations for the high metal concentrations in the Canal, except perhaps for manganese.

The analytical methods used during the survey have inherent characteristics which would possibly yield total metal concentrations in seawater that are somewhat higher than levels reported in the literature. This possibility did not, however, fully explain the magnitude of the apparent discrepancies. Metal levels measured by EPA in Hood Canal were significantly higher than levels observed in various Puget Sound and Hood Canal waters by other investigators, regardless of the techniques used (Chow, 1953; Laevaster, 1954; Tatomer, 1972; Schell and Barnes, 1974). A laboratory investigation was, therefore, initiated in an attempt to explain the discrepant results. All procedures were tested again for repeatability, with reagents and sample containers also being tested for contamination. The laboratory study revealed metal contamination of the sample containers, the acid used to preserve the samples, and the filter flasks used to collect filtrates for dissolved metal analysis. Although the contribution of metal contaminants from the sample containers and acid was relatively small, the filter flasks were a source of considerable contamination in some cases. More importantly, large variations between replicate analyses were observed which reflected a marked loss of analytical precision.

The combined evidence is clear. The lack of agreement between EPA seawater data and that of other investigators; the paradox of possible toxic conditions in the reference areas with no indication of biological harm; and the laboratory results showing possible sample contamination together with a loss of precision led us to discount the seawater metals values. As a result, all EPA seawater metals data were considered suspect and, with the exception of mercury, were omitted from the report because of our inability to verify the accuracy of the findings. In consideration of the intense interest in the mercury content of Liberty Bay waters, certain mercury data, corrected for possible laboratory contamination, were included for discussion.

Metal analyses performed on sediments, fish, and shellfish were demonstrated to be accurate in addition to yielding results that were in reasonable agreement with values obtained by other independent investigators. These data are included in the report without qualification. Work is continuing in an effort to overcome the seawater analytical discrepancies encountered during the survey.

(Mercury)

The concentrations of total mercury measured in Liberty Bay, Hood Canal, and Clam Bay waters during the survey were always <0.7 ug/l. Although this indeterminate mercury level represented a lower limit of detectability that was somewhat higher than the lower limit (0.2 ug/l) described by the analytical method used (EPA, 1975), it was considerably lower than the determinate mercury concentrations (1 - 110 ug/l) reported earlier by Sea Farms, Inc. in Liberty Bay surface waters.

Sediments -

It was recognized at the outset that the analysis of water samples alone would probably reveal little in the way of information on past or recently discontinued practices of discharging wastes to the Liberty Bay system. Sediment samples, and to some extent fish and shellfish, were collected therefore, for the purpose of providing this historical information.

Metal Concentrations

(Surface Sediments) Concentrations of eleven metals measured in surface sediment grab samples collected during the survey are listed in Table 3. Metal concentrations measured in surface sediments at the top of the sediment cores (Table 4) are presented and discussed with the results of the surface sediment grab sample analyses (Figs. 7-17).

Metal concentrations in Liberty Bay surface sediments varied considerably, with higher levels generally being measured in the finer-grained sediments of the central-to-upper Bay. The higher metal content of these sediments was consistent with the demonstration of Crecelius, Bothner, and Carpenter (1975) that concentrations of certain elements (As, Sb, Hg, Fe, and C) in "noncontaminated" Puget Sound surface sediments tended to increase as the mean grain size of the sediments decreased. The elevated metal concentrations characterizing sediments behind the Poulsbo marina breakwater would be expected, therefore, considering the influence of reduced current velocities in the area on the distribution and accumulation of finer-grained materials containing or consisting of metal contaminants as well as "noncontaminated" sediments. The detection of the highest concentrations of certain metals (Cd, Cr, Pb and Zn) in the coarser-grained sediments near the Torpedo Station plating plant overflow outfall and industrial storm sewer system was not surprising,

Table 3. Concentrations of Metals in Surface Sediments from Liberty Bay, Clam Bay and Hood Canal.

Station	Date	Concentration µg/g (dry weight)										
		Antimony (Sb)	Arsenic (As)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Manganese (Mn)	Mercury (Hg)	Nickel (Ni)	Zinc (Zn)
Liberty Bay Stations												
WS-0 (Dogfish Creek)	10-7-75	0.080	6.0	0.60	16	5.5	12,000	5.6	160	0.030	24	38
S-2 (Upper Bay)	9-15-75	0.10	12	4.2	52	39	25,000	25	230	0.14	58	100
WSF-3 (Near Poulsbo STP Outfall)	9-15-75	0.20	8.0	2.8	33	29	18,000	18	170	0.11	51	65
S-4 (Northwest Bay)	9-15-75	<0.10	11	3.1	50	31	23,000	25	220	0.14	56	92
WSF-5 (Oyster Hatchery Site)	9-15-75	<0.10	11	13	52	65	32,000	93	310	0.18	110	240
WS-7 (Central Bay)	9-15-75	<0.10	13	3.6	45	45	28,000	46	250	0.16	64	120
S-8 (West Central Bay)	9-15-75	<0.10	10	3.1	42	31	19,000	31	200	0.13	59	94
S-9 (East Central Bay)	9-15-75	<0.10	5.0	1.2	17	7.9	10,000	12	120	0.047	24	33
WSF 13 (Keyport STP Outfall)	9-15-75	<0.10	5.0	1.7	21	13	12,000	23	110	0.077	23	52
SF-16 (NTS[a] STP Outfall)	9-17-75	<0.10	4.0	2.5	22	19	12,000	20	130	0.092	30	58
WS-17 (NTS Paint Shop Storm Sewer Outfall)	9-17-75	<0.02	4.0	2.7	27	17	14,000	22	180	0.055	44	55
S-18 (Beach Below NTS Mid-Storm Sewer Outfall)	9-17-75	0.40	3.1	5.1	180	55	17,000	190	230	0.027	52	360
WSF-19 (Near NTS Plating Plant Overflow Outfall)	9-17-75	<0.10	5.0	2.9	55	17	16,000	20	190	0.077	49	71
S-20 (Beach Below NTS Plating Plant Overflow Outfall)	9-17-75	0.70	2.0	24	55	55	14,000	60	210	0.023	55	120
S-21 (Below NTS S.E. Lagoon)	9-17-75	<0.10	10	1.9	42	55	23,000	47	190	0.11	66	160
WS-22 (NTS S.E. Lagoon)	9-17-75	<0.10	3.0	0.70	21	44	15,000	22	170	0.029	40	46
WS-23 (NTS N.W. Lagoon)	10-10-75	0.29	11	0.90	31	27	200	42	410	0.14	36	75
S-24 (Below NTS N.W. Lagoon)	9-17-75	<0.10	6.0	2.6	27	21	18,000	52	200	0.046	52	65
Reference Stations												
Hood Canal (Misery Pt.)	9-16-75	<0.10	7.0	1.2	28	21	18,000	6.0	490	0.026	51	54
Clam Bay	9-16-75	3.5	6.0	1.0	22	21	12,000	31	104	0.097	18	100

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[a] NTS Navy Torpedo Station

however, considering the Navy's approximate 40-year history of discharging untreated plating wastes from the Torpedo Station to nearby marine waters.

Antimony concentrations in Liberty Bay surface sediments usually ranged from <0.02 - 0.70 ug/g (Fig. 7). These values were generally considerably lower than the levels (0.3 - 1.0 ug/g) detected in "noncontaminated" Puget Sound surface sediments by Crecelius and his associates (1975).

An average high concentration of 2.6 ug/g was measured behind the Poulsbo marina breakwater (Station C-F). Although this level was similar to the concentrations measured at the Clam Bay reference station (3.5 ug/g) and at several other central Puget Sound sites, it was well below levels measured near the Tacoma smelter (Crecelius et al., 1975).

Arsenic concentrations in surface sediments from the Liberty Bay system ranged from 2.0 - 16 ug/g (Fig. 8). This range was similar to the range of arsenic levels (3 - 15 ug/g) reported by Crecelius and co-workers (1975) in "noncontaminated" surface sediments collected from throughout Puget Sound. It also corresponded to the range reported by Huntamer and Schell (1974) in surface sediments from Colvos Passage and Commencement Bay.

Although arsenic levels tended to be higher in those sediments having a higher mud content, even the higher concentrations were considerably lower than arsenic levels measured by Crecelius and his associates (1975) in sediments collected in the vicinity of the Tacoma smelter. The smelter was considered to be the major man-induced source of arsenic and antimony to Puget Sound.

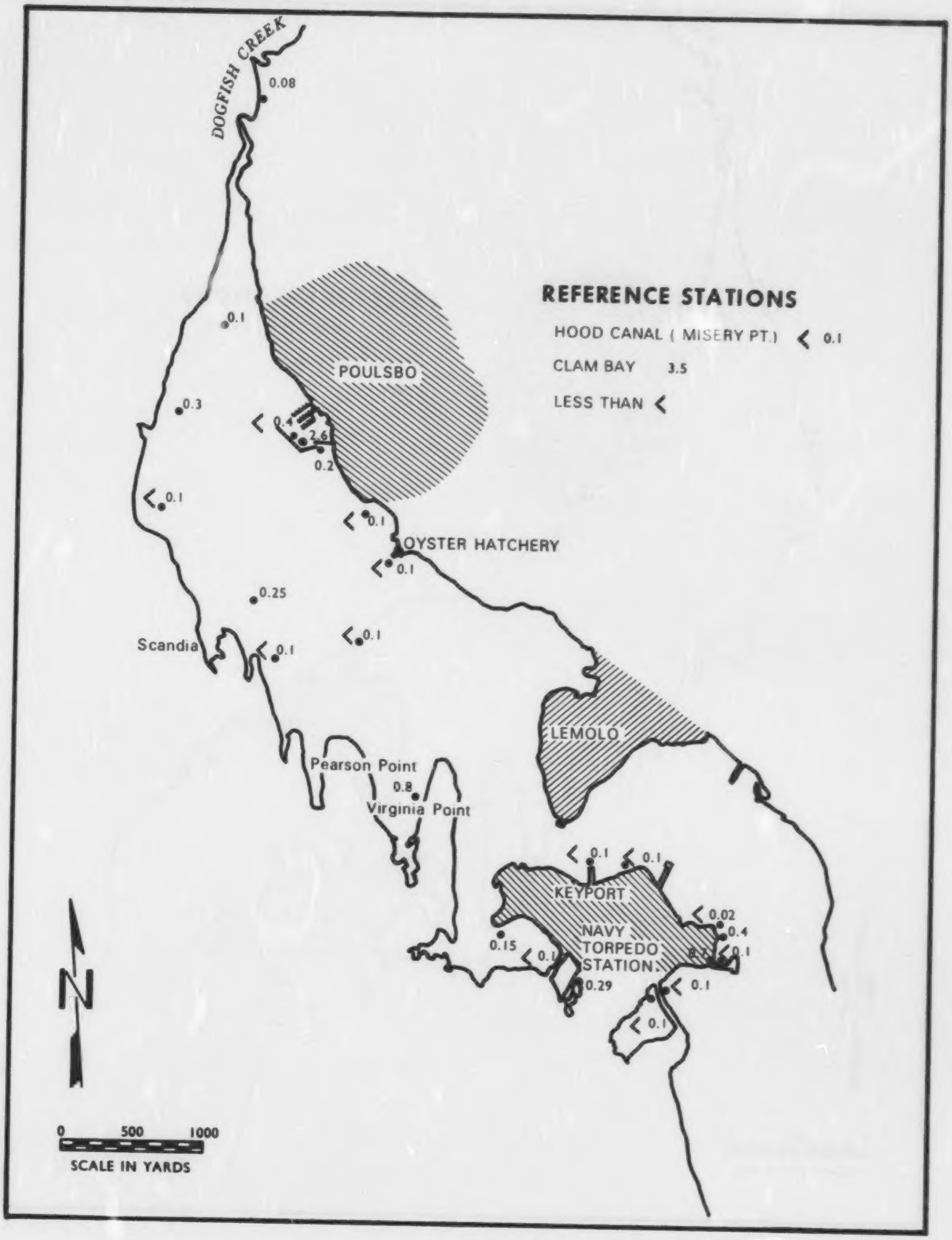

DOGFISH CREEK
0.08
0.1
POULSBO
0.3
< 0.4
2.6
0.2
< 0.1
< 0.1
OYSTER HATCHERY
< 0.1
0.25
< 0.1
Scandia
< 0.1
LEMOLO
Pearson Point
0.8
Virginia Point
< 0.1
< 0.1
KEYPORT
NAVY
TORPEDO
STATION
< 0.02
0.4
< 0.1
0.15
< 0.1
0.29
< 0.1
< 0.1
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) < 0.1
CLAM BAY 3.5
LESS THAN <
N
0
500
1000
SCALE IN YARDS

Figure 7. Antimony concentrations in Liberty Bay surface sediments (ug/g dry weight).

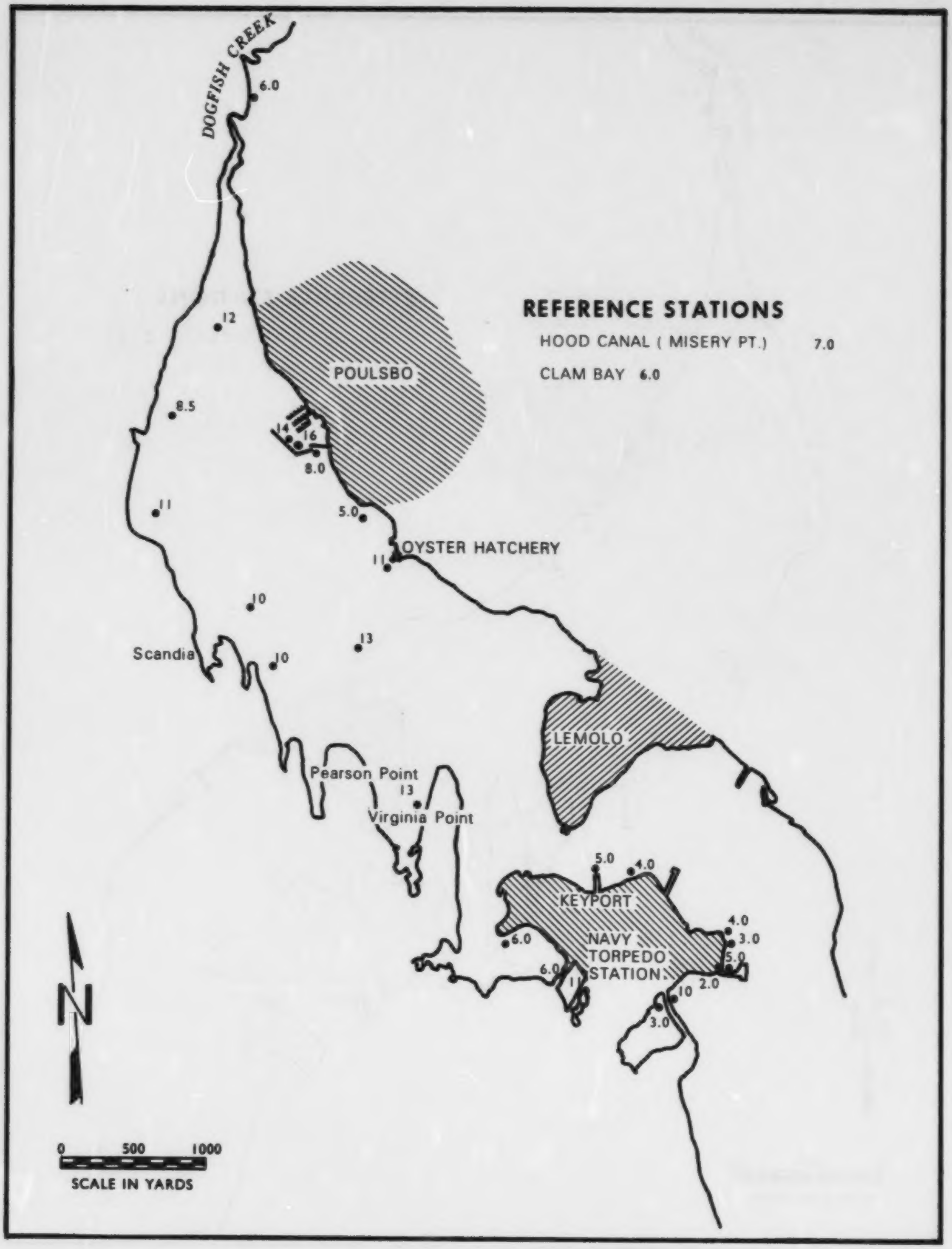

DOGFISH CREEK
6.0
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) 7.0
CLAM BAY 6.0
12
POULSBO
8.5
14
16
8.0
11
5.0
OYSTER HATCHERY
11
10
13
Scandia
10
LEMOLO
Pearson Point
13
Virginia Point
5.0
4.0
KEYPORT
NAVY TORPEDO STATION
6.0
6.0
11
4.0
3.0
5.0
2.0
10
3.0
N
0
500
1000
SCALE IN YARDS

Figure 8. Arsenic concentrations in Liberty Bay surface sediments (ug/g dry weight).

Cadmium - Most cadmium levels in Liberty Bay sediments ranged from 0.70 - 5.1 ug/g, with concentrations within this range being somewhat higher in the upper Bay (Fig. 9). A high concentration of 24 ug/g was measured in the sediment below the Torpedo Station plating plant overflow outfall. This observation, coupled with the results of the Compliance Monitoring Inspection (EPA, 1975), indicated that the plating plant was at least one major source of cadmium to the system. The inspection also showed that relatively small amounts of cadmium were being added by the Poulsbo and Keyport STPs as well as the Torpedo Station paint shop storm sewer.

An interesting feature characterizing, to varying degrees, the distribution of cadmium, as well as copper, lead, iron, manganese, mercury, nickel, zinc, and to some extent chromium, was the relatively high metal concentration measured at the Sea Farms hatchery site (Station WSF-5) compared to most other stations outside the Poulsbo marina breakwater, including those stations located in proximity of the Torpedo Station. In the case of cadmium, the 13 ug/g concentration measured at Station WSF-5 actually exceeded the average concentration (4.3 ug/g) measured inside the Marina breakwater. In most cases, however, the metal concentrations detected at the hatchery site were remarkably similar to those levels measured inside the breakwater. The reason for this similarity is not well understood. It suggests, however, that certain features characterizing the hatchery site, such as its proximity to the deep basin to the south, as well as the pier structure and protruding shoreline, may have had an effect on the rate of sedimentation

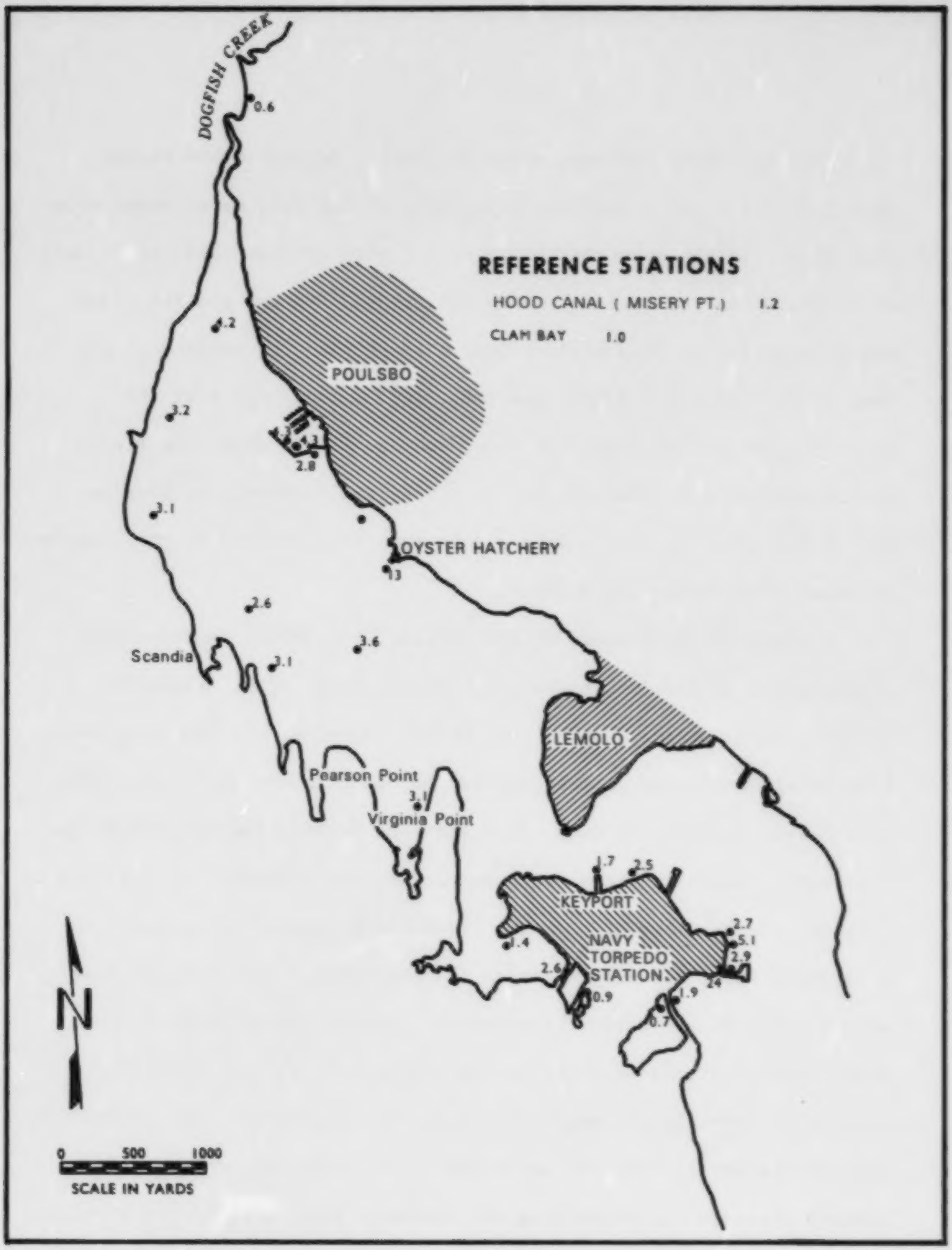

DOGFISH CREEK
0.6
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) 1.2
CLAM BAY 1.0
4.2
POULSBO
3.2
4.3
2.8
3.1
OYSTER HATCHERY
13
2.6
Scandia
3.6
3.1
LEMOLO
Pearson Point
3.1
Virginia Point
1.7
2.5
KEYPORT
2.7
5.1
2.9
1.4
NAVY
TORPEDO
STATION
2.6
0.9
1.9
24
0.7
N
0
500
1000
SCALE IN YARDS

Figure 9. Cadmium concentrations in Liberty Bay surface sediments (ug/g dry weight).

and particle size distribution that was similar to that of the Poulsbo marina breakwater. Although the similarity in metal concentrations at both locations also suggests that the metals came from common sources, the possibility that different sources were involved cannot be discounted.

Chromium concentrations ranged from 17 - 180 ug/g, with the distribution generally following the pattern discussed earlier (Fig. 10). This range was similar to the range of chromium levels (43 - 199 ug/g) reported by Crecelius and associates (1975) in surface sediments from the Puget Sound region.

The highest chromium concentration (180 ug/g) was measured in surface sediments collected below the Torpedo Station mid-storm sewer outfall (Station S-18). This concentration, as well as the relatively high levels of other metals (Cu, Pb, Zn) in the surface sediment below the mid-storm sewer outfall, was believed to be associated with used sand-blasting sand that was dumped or washed into the sewer system by Navy personnel (Personal Communication, Dick Boughner, U.S. Navy, Seattle, WA).

Copper levels ranged from 7.9 - 70 ug/g in surface sediments throughout the Liberty Bay system (Fig. 11). The highest concentrations were measured in the surface sediments behind the Poulsbo marina breakwater (70 ug/g) and at the Sea Farms hatchery site (65 ug/g), with somewhat elevated levels (55 ug/g) detected in the vicinity of the Torpedo Station. Intermediate Liberty Bay copper concentrations were generally higher than the levels measured in Colvos Passage sediments

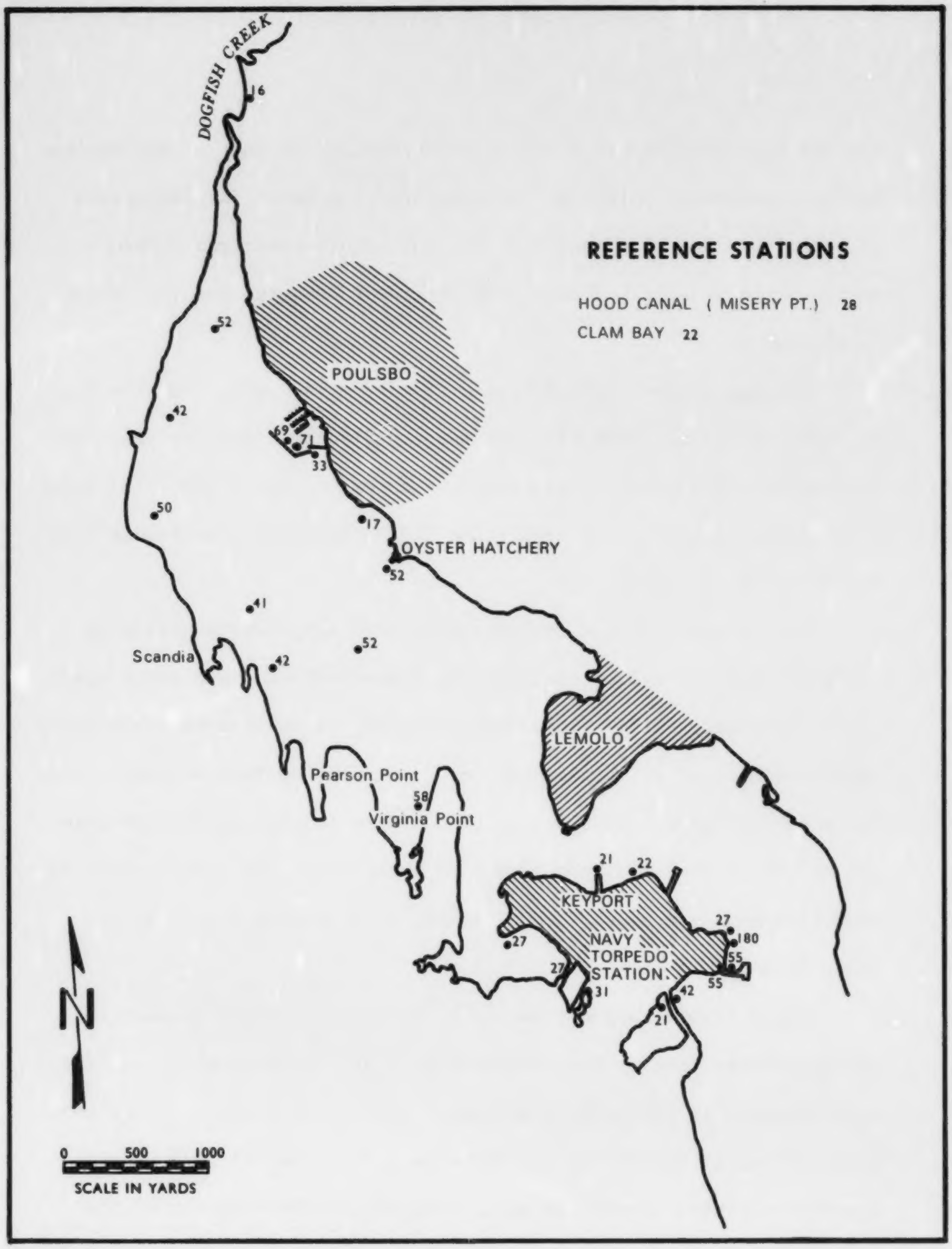

DOGFISH CREEK
16
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) 28
CLAM BAY 22
52
POULSBO
42
69
71
33
50
17
OYSTER HATCHERY
52
41
52
Scandia
42
LEMOLO
Pearson Point
58
Virginia Point
21
22
KEYPORT
27
180
27
NAVY TORPEDO STATION
55
27
55
31
42
21
N
0 500 1000
SCALE IN YARDS

Figure 10. Chromium concentrations in Liberty Bay surface sediments (ug/g dry weight).

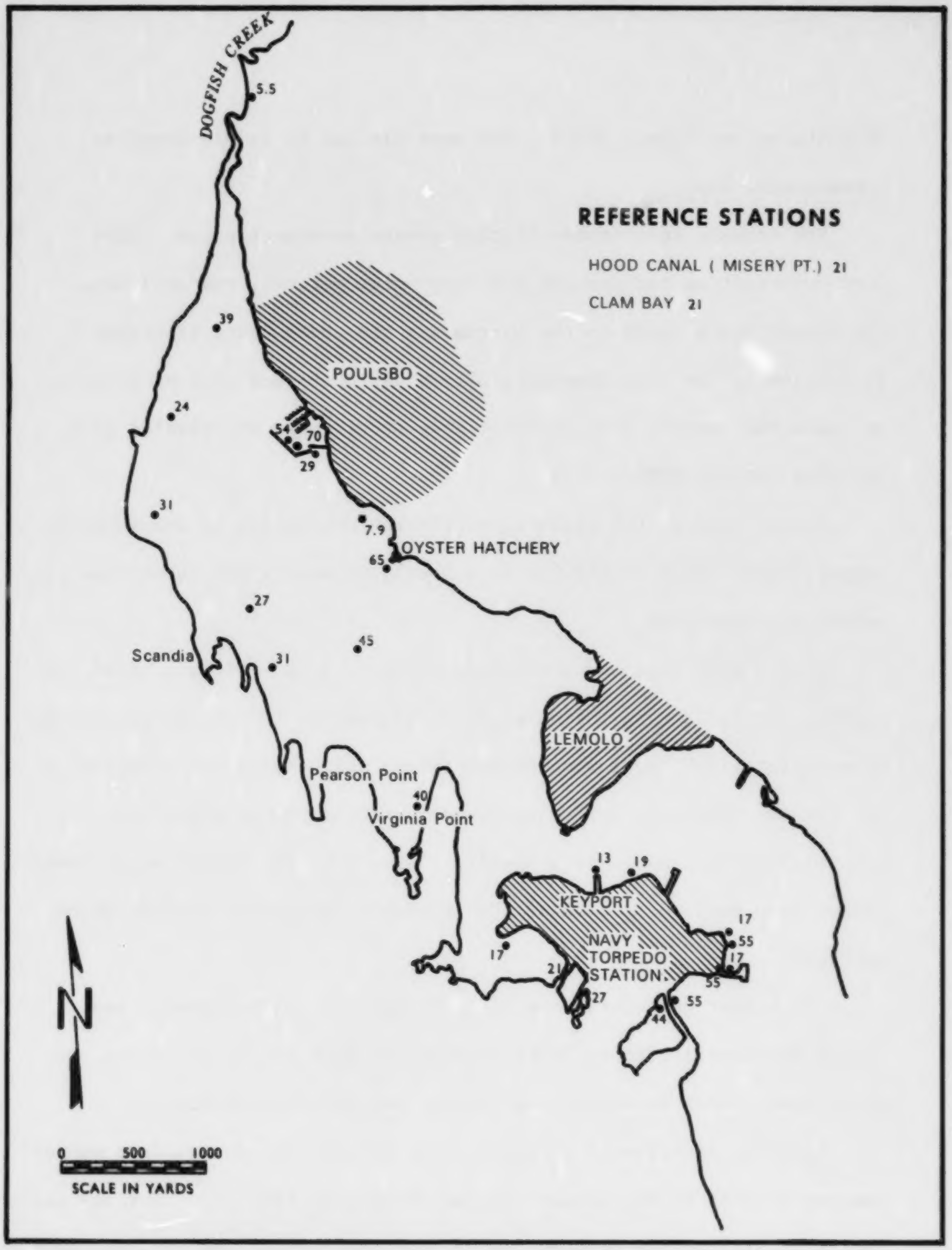

DOGFISH CREEK
5.5
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) 21
CLAM BAY 21
39
POULSBO
24
54
70
29
31
7.9
OYSTER HATCHERY
65
27
45
Scandia
31
LEMOLO
Pearson Point
40
Virginia Point
13
19
KEYPORT
NAVY
TORPEDO
STATION
17
17
55
17
21
55
27
55
44
N
0
500
1000
SCALE IN YARDS

Figure 11. Copper concentrations in Liberty Bay surface sediments (ug/g dry weight).

by Huntamer and Schell (1974), but were similar to levels found in Commencement Bay.

The Poulsbo and Torpedo Station sewage treatment plants (STPs) were contributing forty-eight and forty-nine percent, respectively, of the copper being added to the system via the three waste treatment facilities in the area (Appendix B). Other confirmed sources of copper included the Torpedo Station paint shop storm sewer and plating plant overflow outfall (EPA, 1975).

Copper lost in the vicinity of the Poulsbo marina in the form of copper-based bottom paints may be a localized source but quantities cannot be determined.

Iron - Most iron concentrations ranged from 8 - 32 mg/g, with the highest level (38 mg/g) being measured behind the Poulsbo marina breakwater (Fig. 12). The lowest concentration (0.20 mg/g) was measured in the Torpedo Station's northwest lagoon. The sample on which this low determination was made was primarily composed of the lagoon's clay bank rather than surface sediments, thus possibly explaining the low value obtained.

The higher concentrations of iron measured in the Liberty Bay system were similar to or lower than levels measured by Crecelius and associates (1975) in surface sediments throughout Puget Sound.

Lead was distributed throughout the Liberty Bay system in a manner similar to that of the metals already discussed (Fig. 13). Surface sediments at Station S-9 between the Poulsbo STP outfall and the Sea Farms hatchery site contained only 12 ug/g, while the highest lead level (190 ug/g) was measured below the Torpedo Station in mid-storm sewer

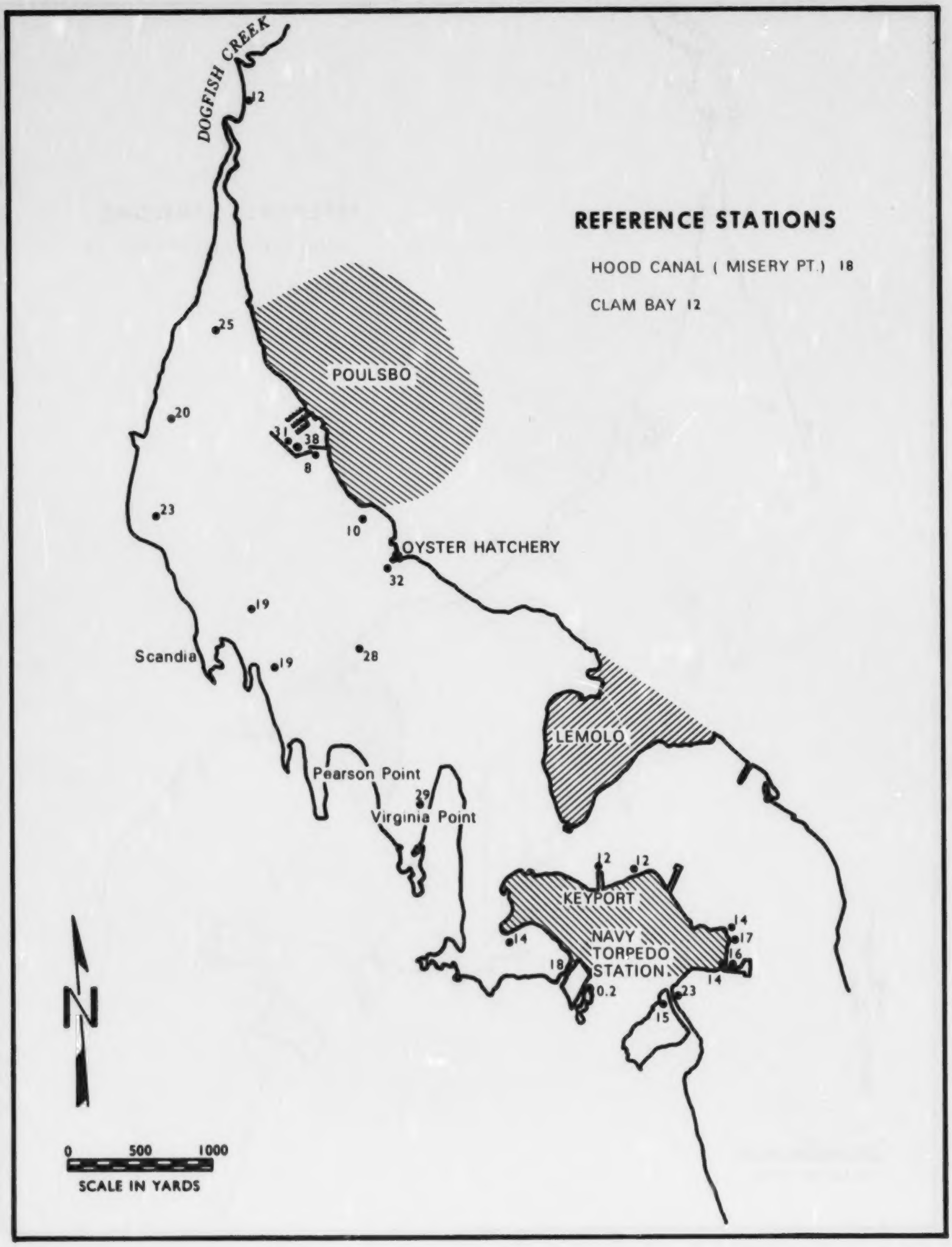

DOGFISH CREEK
12
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) 18
CLAM BAY 12
25
POULSBO
20
31
38
8
23
10
OYSTER HATCHERY
32
19
Scandia
19
28
LEMOLO
Pearson Point
29
Virginia Point
12
12
KEYPORT
NAVY TORPEDO STATION
14
14
17
16
14
18
0.2
23
15
N
0
500
1000
SCALE IN YARDS

Figure 12. Iron concentrations in Liberty Bay surface sediments (mg/g dry weight).

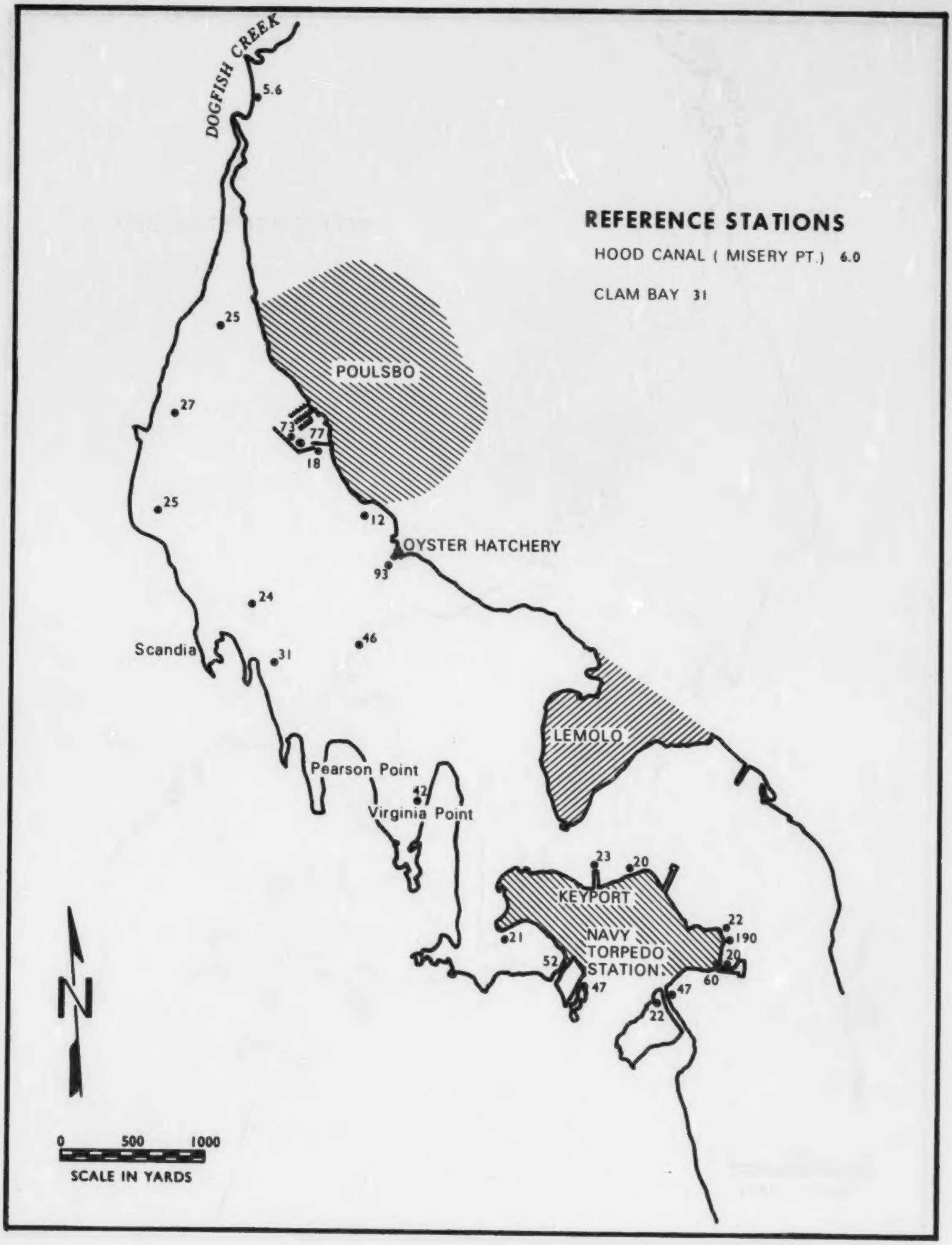

DOGFISH CREEK
5.6
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) 6.0
CLAM BAY 31
25
POULSBO
27
73
77
18
25
12
OYSTER HATCHERY
93
24
Scandia
46
31
LEMOLO
Pearson Point
42
Virginia Point
23
20
KEYPORT
22
190
21
NAVY TORPEDO STATION
20
52
60
47
47
22
N
0
500
1000
SCALE IN YARDS

Figure 13. Lead concentrations in Liberty Bay surface sediments (ug/g dry weight).

outfall (Station S-18). Most of the lead concentrations were somewhat higher than reported by Huntamer and Schell (1974) in sediments from Colvos Passage, but were similar to levels measured by them in sediment collected from Commencement Bay.

As mentioned earlier, one source of lead to the Liberty Bay system was believed to be used sandblasting sand from the Torpedo Station. Other potentially important sources included the Poulsbo STP, as well as the Torpedo Station paint shop storm sewer and plating plant.

Manganese levels ranged from 110 - 410 ug/g throughout the Liberty Bay system (Fig. 14). Although relatively high manganese concentrations were measured behind the Poulsbo marina breakwater and at the Sea Farms hatchery site (300 - 310 ug/g), the highest level (410 ug/g) was found in the Torpedo Station's northwest lagoon (Station WS-23). This value may have been related to the high clay content of the sample collected at the station rather than to any local source of contamination. The manganese concentration measured at the Hood Canal (Misery Point) reference station (490 ug/g) may also have reflected the influence of local geologic characteristics. Interestingly, a large number of manganese deposits exist on the Olympic Peninsula just west of Hood Canal (U.S. Geological Survey, 1966).

Mercury concentrations in surface sediments throughout the Liberty Bay system ranged from a low of 0.023 ug/g below the Torpedo Station plating plant overflow outfall (Station S-20) to a high of 0.37 ug/g behind the Poulsbo marina breakwater. The concentration of mercury at the Sea Farms hatchery site (Station WSF-5) was 0.18 ug/g (Fig. 15).

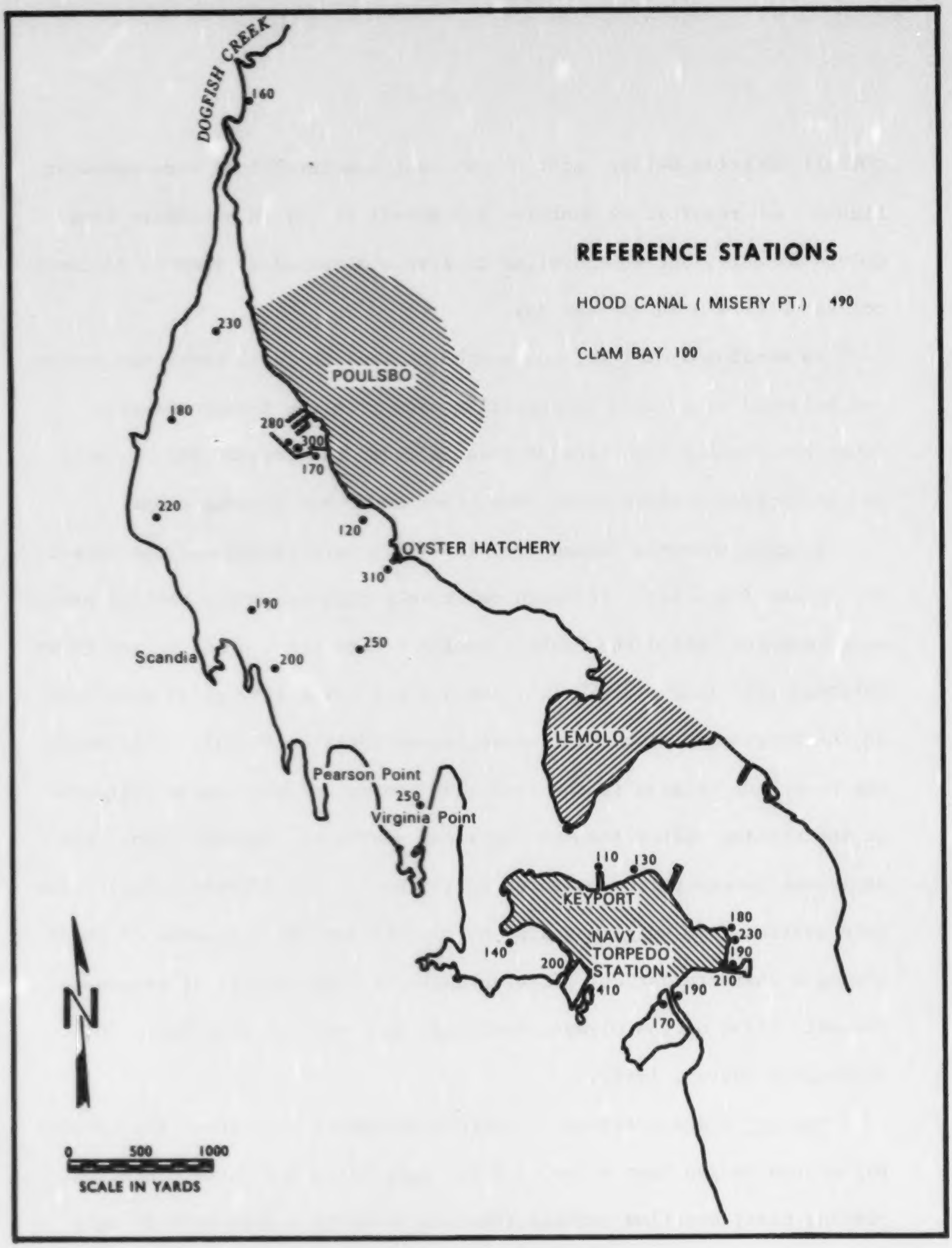

DOGFISH CREEK
160
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) 490
CLAM BAY 100
230
POULSBO
180
280
300
170
220
120
OYSTER HATCHERY
310
190
250
Scandia
200
LEMOLO
Pearson Point
250
Virginia Point
110
130
KEYPORT
180
230
190
NAVY TORPEDO STATION
140
200
210
410
190
170
N
0
500
1000
SCALE IN YARDS

Figure 14. Manganese concentrations in Liberty Bay surface sediments (ug/g dry weight).

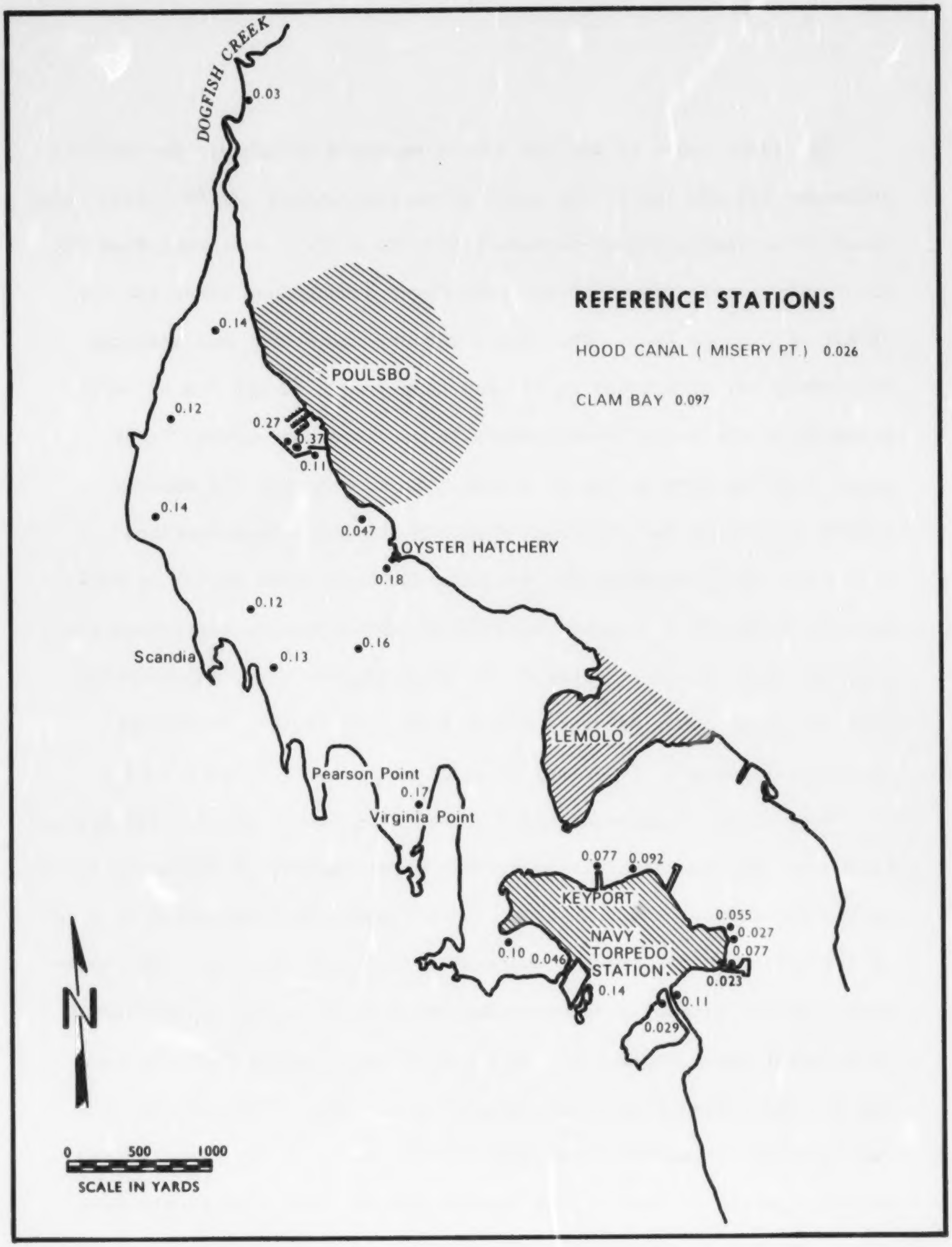

DOGFISH CREEK
0.03
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) 0.026
CLAM BAY 0.097
0.14
POULSBO
0.12
0.27
0.37
0.11
0.14
0.047
OYSTER HATCHERY
0.18
0.12
0.16
Scandia
0.13
LEMOLO
Pearson Point
0.17
Virginia Point
0.077
0.092
KEYPORT
NAVY
TORPEDO
STATION
0.055
0.027
0.077
0.023
0.10
0.046
0.14
0.11
0.029
N
0
500
1000
SCALE IN YARDS

Figure 15. Mercury concentrations in Liberty Bay surface sediments (ug/g dry weight).

The lower range of mercury levels measured in Liberty Bay surface sediments was similar to the range of concentrations (0.009 - 0.15 ug/g) found by Crecelius and co-workers (1975) in surface sediments from the relatively remote waters of northern Puget Sound, Hood Canal and the Strait of Juan de Fuca. The higher mercury concentrations measured in Liberty Bay were equal to or less than levels (0.069 - 0.52 ug/g) measured by the above investigators in southern and central Puget Sound of which Liberty Bay is a part. In no case did the mercury levels in Liberty Bay sediments approach the high concentrations (4.0 - 100 ug/g) detected by Crecelius and associates (1975) in surface sediments in Bellingham Bay. These investigators attributed the source of this mercury contamination to a mercury cell, chlor-alkali plant in Bellingham, Washington that from 1965 to 1971 discharged substantial amounts of mercury to Bellingham Bay on a daily basis.

Just as the results of the chemical analysis of Liberty Bay waters failed to show any significant mercury contamination of the water column during the survey, the results of the sediment analyses failed to point to any major past or present sources of such contamination. The somewhat elevated mercury concentrations measured along the entire length of sediment cores collected from the upper Bay, particularly behind the Poulsbo marina breakwater, suggested, however, that relatively small amounts of mercury had entered the Liberty Bay system over an extended period of time. This observation was confirmed by the Compliance Monitoring Inspection (EPA, 1975) which found small quantities of mercury being added to the system via the sewage treatment facilities in the area as well as from the Torpedo Station plating plant overflow outfall and paint shop storm sewer. Mercury contributed by the STPs was approximately evenly split between the Poulsbo plant (0.0007 lbs (0.00032 kg)/day; 46%) and Torpedo Station facility (0.0008 lbs (0.00036 kg)/day; 52%).

The concentrations of mercury measured in the STP effluents (0.2 - 1.2 ug/l) as well as in the Torpedo Station plating plant overflow (0.3 ug/l) and paint shop storm sewer (3.8 ug/l) were in general agreement with the levels of mercury reported by Young (1974) in several municipal wastewater effluents being discharged to southern California marine waters. The importance of industrial-domestic sewage treatment facilities as contributors of substantial quantities of mercury and other metals to Puget Sound waters has also been recognized for some time. Crecelius and his associates (1975) estimated that prior to 1973, METRO's West Point sewage treatment plant annually discharged 420 kg of mercury, 250 kg of antimony, and 800 kg of arsenic to the central Puget Sound basin.

Few, if any, commercially important deposits of mercury ore (cinnabar) are located near marine waters of the State of Washington (U.S. Geological Survey, 1966). Although noncommercial mercury ores appear to be associated with manganese ore deposits on the northwestern Olympic Peninsula, such ores would not be a direct source of mercury to the Liberty Bay system.

Nickel concentrations in Liberty Bay surface sediments ranged from 23 ug/g near the Keyport STP outfall to a high of 112 ug/g behind the Poulsbo marina breakwater (Fig. 16). With the exception of the

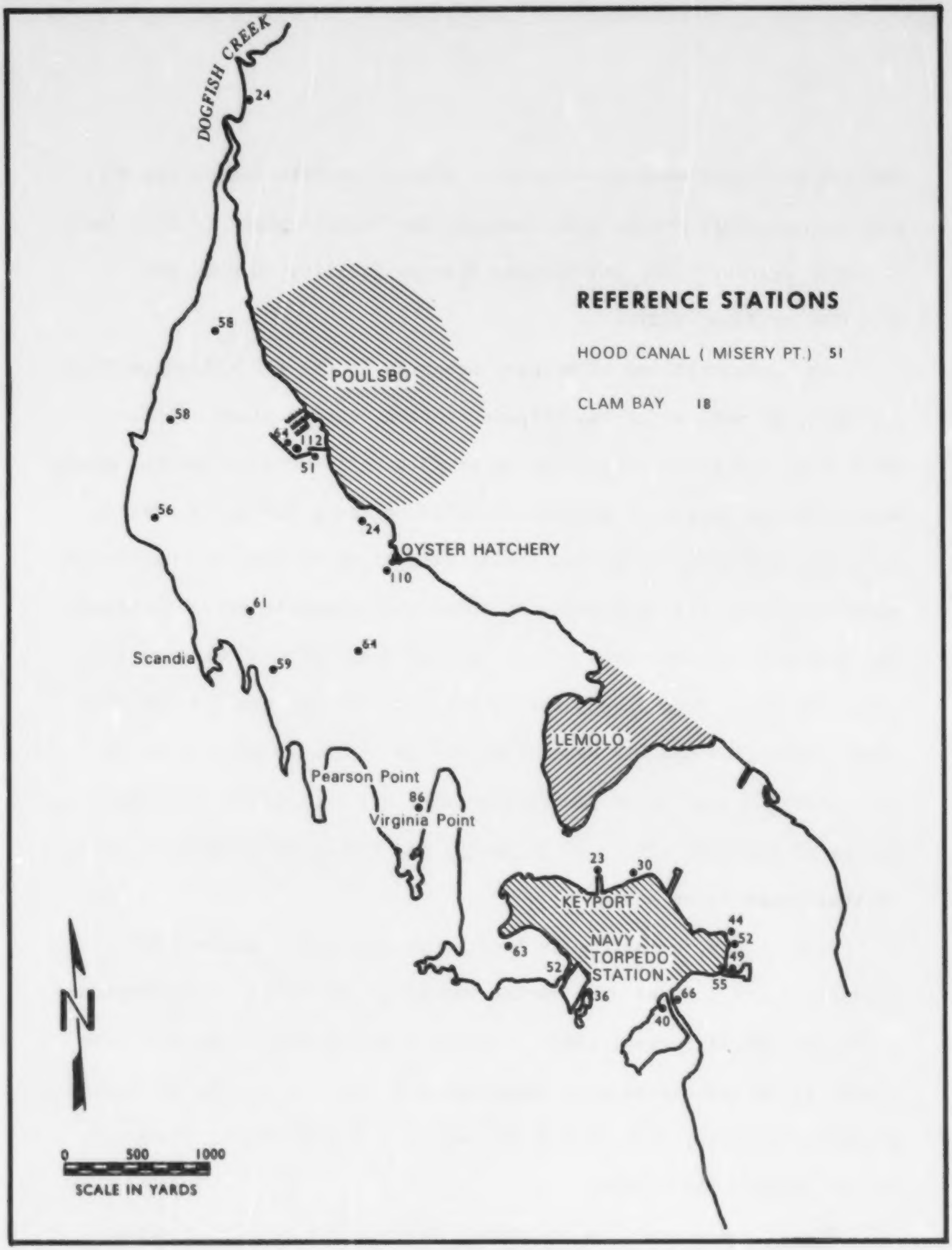

DOGFISH CREEK
24
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) 51
CLAM BAY 18
58
POULSBO
58
64
112
51
56
24
OYSTER HATCHERY
110
61
64
Scandia
59
LEMOLO
Pearson Point
86
Virginia Point
23
30
KEYPORT
44
52
49
55
NAVY TORPEDO STATION
63
52
36
66
40
N
0
500
1000
SCALE IN YARDS

Figure 16. Nickel concentrations in Liberty Bay surface sediments (ug/g dry weight).

relatively high nickel levels measured behind the marina breakwater and at the Sea Farms hatchery site (110 ug/g), most nickel concentrations fell within the range of values (25 - 80 ug/g) reported by Huntamer and Schell (1974) in surface and near-surface sediments from Colvos Passage.

Major potential sources of nickel to Liberty Bay included the Torpedo Station STP (Appendix B) and the Station's plating plant overflow bypass (EPA, 1975).

Zinc levels in Liberty Bay surface sediments ranged from 33 ug/g at Station 9 to 360 ug/g below the Torpedo Station's mid-storm sewer (Station S-18). Relatively high zinc concentrations were also measured behind the Poulsbo marina breakwater (180-250 ug/g) and at the Sea Farms hatchery site (240 ug/g) (Fig. 17).

The occurrence of high zinc levels below the mid-storm sewer again points to the used sandblasting sand as a possible significant source of zinc to the system. Other potentially important sources included the local STPs (Appendix B) as well as the Torpedo Station plating plant overflow outfall and paint shop storm sewer (EPA, 1975). Interestingly, the Poulsbo STP was contributing fifty-six percent of the STP-associated zinc, while the Torpedo Station and Keyport STPs were contributing twenty-nine and fifteen percent, respectively.

(Sediment Cores) The results of the metal analyses performed on the sediment cores are presented in Table 4. Analysis of the core tops, as well as the middle and bottom sections, yielded results that were generally characterized by considerable variation between replicate core samples. This variation made it difficult to determine whether

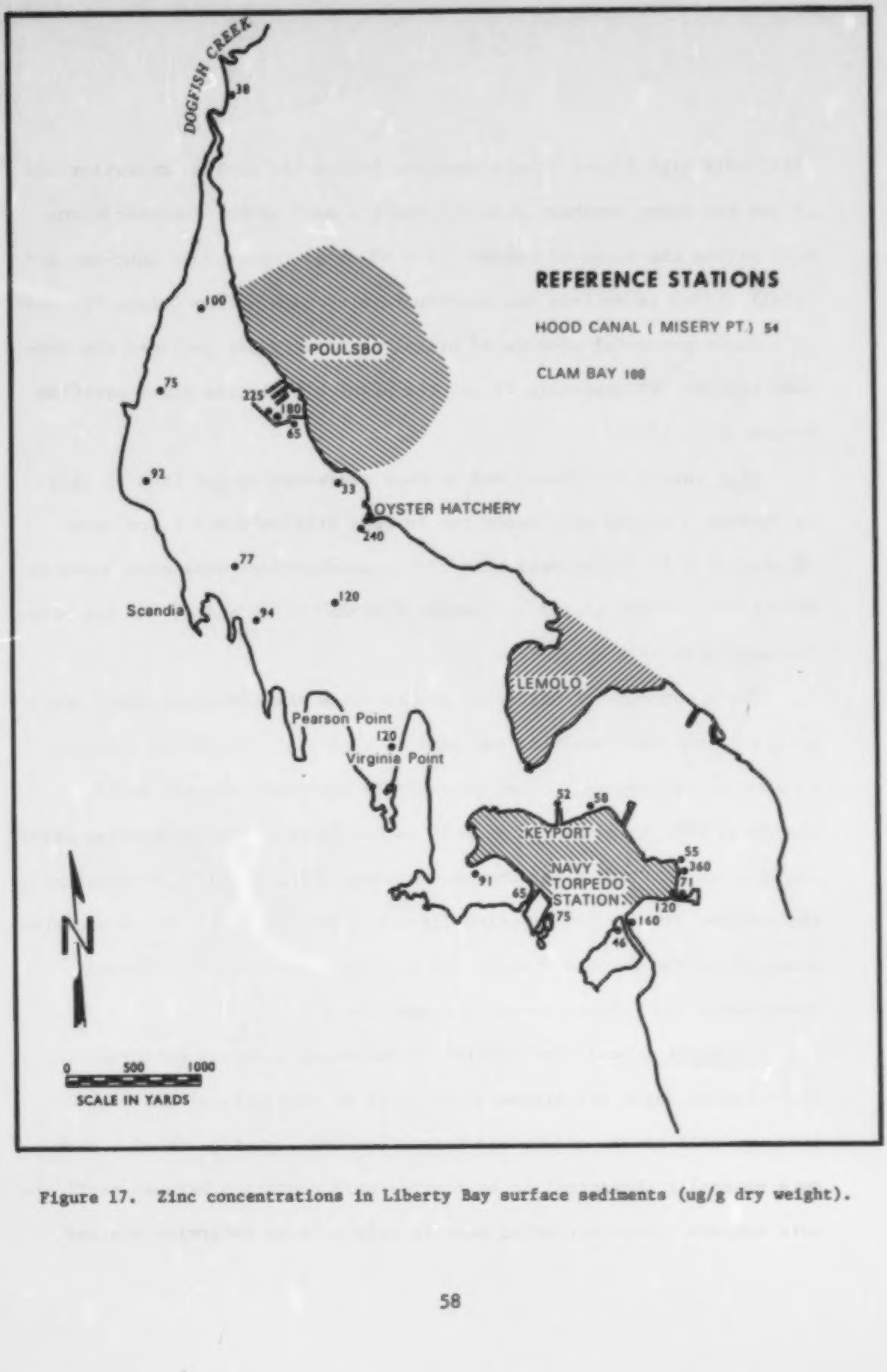

DOGFISH CREEK
38
100
75
225
180
65
92
33
OYSTER HATCHERY
240
77
120
Scandia
94
POULSBO
LEMOLO
Pearson Point
120
Virginia Point
52
58
KEYPORT
NAVY TORPEDO STATION
55
360
71
91
65
75
120
160
46
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) 54
CLAM BAY 100
N
0
500
1000
SCALE IN YARDS

Figure 17. Zinc concentrations in Liberty Bay surface sediments (ug/g dry weight).

Table 5. Concentrations of Metals in Sediment Cores Collected from Liberty Bay.

Station	Replicate Core Number	Core Sample Location[a]	Antimony (Sb)	Arsenic (As)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Manganese (Mn)	Mercury (Hg)	Nickel (Ni)	Zinc (Zn)	Core Length cm	Sediment Penetration cm
			Concentration µg/g (dry weight)												
C - A	1	T	<0.10	14	4.6	73	54	31,000	60	270	0.23	69	130	37	50
		M	0.70	14	4.0	64	58	31,000	61	280	0.26	77	180		
		B	0.80	18	4.4	60	60	33,000	54	300	0.36	110	150		
(Poulsbo Marina)	2	T	0.70	16	4.0	64	53	30,000	66	280	0.30	39	300	34	48
		M	0.60	12	4.1	64	60	29,000	68	290	0.30	50	250		
		B	0.70	12	4.9	78	55	33,000	59	310	0.28	93	150		
C - F	1	T	4.2	15	4.2	73	61	41,000	83	300	0.37	55	150	25	41
		M	1.1	18	4.1	60	100	29,000	60	300	0.35	55	190		
		B	0.80	13	3.3	52	59	30,000	24	280	0.12	50	120		
(Poulsbo Marina)	2	T	0.90	17	4.3	68	78	38,000	70	300	0.37	170	210	18	43
		M	0.60	15	5.0	67	62	28,000	63	[illegible]	0.46	63	150		
		B	0.80	19	4.4	70	63	30,000	56	310	0.27	56	210		
C - B	1	T	0.20	8.0	3.0	60	23	19,000	31	180	0.10	70	76	16	33
		M	0.40	9.0	2.6	61	23	21,000	32	180	0.12	51	83		
		B	0.44	7.0	3.3	61	18	20,000	19	210	0.12	62	70		
(Upper West Bay)	2	T	0.40	9.0	3.3	66	24	21,000	30	170	0.13	36	73	17	33
		M	0.30	10	2.9	63	26	19,000	29	170	0.13	75	80		
		B	0.30	8.0	2.6	64	17	15,000	19	170	0.11	77	94		
C - C	1	T	0.40	15	3.5	60	41	26,000	30	230	0.15	70	110	23	30
		M	0.40	14	3.5	51	39	27,000	35	230	0.12	82	100		
		B	0.60	10	3.3	44	32	24,000	33	240	0.15	40	86		
(Central West Bay)	2	T	0.10	5.0	1.7	21	13	12,000	12	120	0.082	46	44	19	25
		M	6.0	10	1.7	21	12	13,000	17	110	0.087	31	51		
		B	0.20	5.0	1.3	26	11	11,000	14	130	0.059	18	41		
C - D	1	T	1.0	13	3.1	57	43	29,000	43	260	0.17	110	120	24	50
		M	0.70	10	2.7	46	34	25,000	36	210	0.21	100	110		
		B	0.60	10	3.4	44	20	23,000	14	230	0.054	38	100		
(Lower West Bay)	2	T	0.60	12	3.1	59	37	29,000	41	230	0.17	62	110	26	51
		M	0.50	9.0	3.7	49	36	25,000	28	220	0.15	80	100		
		B	0.60	9.0	3.7	48	28	26,000	15	240	0.20	40	77		
C - E	1	T	0.20	5.0	1.1	18	10	10,000	8.3	120	0.052	36	72	19	28
		M	0.30	8.0	1.1	27	14	13,000	17	140	0.074	65	48		
		B	0.20	7.0	1.6	25	11	12,000	20	140	0.10	20	41		
(Lower West Bay)	2	T	0.10	7.0	1.6	35	24	18,000	33	160	0.14	90	110	17	23
		M	0.10	5.0	1.1	24	12	13,000	11	120	0.083	24	45		
		B	0.20	5.0	1.2	27	6.9	10,000	8.6	110	0.086	17	34		

[a] T Top of core
M Middle of core
B Bottom of core

or not vertical concentration gradients of selected metals were present at many of the stations. For the purpose of this report, concentration gradients were considered to possibly exist at a station only when a definite gradient trend was observed in both replicate samples. Although most of the metals failed to exhibit vertical concentration gradients at most of the stations, weak to strong gradients of all the metals were observed at one or more of the core sites. The metal levels measured throughout many of the cores were generally elevated compared to metal levels in the Hood Canal surface sediment reference sample.

One of the purposes of analyzing sediment cores was to determine if mercury compounds reportedly applied to oyster beds in 1949 and 1950 to control oyster drills were in high enough concentrations in the sediments to have possibly been the source of the high mercury concentrations reported in Liberty Bay waters. Because the time intervals covered by the cores could not be determined without additional information, it was not known whether or not the cores included sediments deposited during the period of interest. The relatively short half life of mercury reported by Crecelius and his associates (1975) in Bellingham Bay surface sediments, coupled with the knowledge that only small amounts of mercuric chloride were actually applied to the oyster beds suggested, however, that the sediments involved were a very unlikely source of high mercury concentrations in Liberty Bay waters. This tended to be confirmed by the relatively low mercury levels measured in all the cores.

The generally higher and more stable concentrations of most of the metals measured behind the Poulsbo marina breakwater (Stations C-A and

C-F) are believed to have reflected the relatively rapid accumulation of sediments in which the metal concentrations had come into equilibrium with relatively constant sources of metal contamination. If the Torpedo Station had historically been one of the several point source discharges contributing significant quantities of metals to the marina sediments, a decline in surface sediment metal concentrations might have been expected after treatment of the Torpedo Station plating plant wastes was begun in February 1975. Nickel concentrations did appear to be lower in surface sediments than at depth at Station C-A; however, the reason for this trend was unclear considering the apparent increase in copper, lead, and mercury levels near the surface of Station C-F. Continued monitoring of metal concentrations in Liberty Bay sediments would provide a means of determining the significance of past contributions of metals from the Torpedo Station and other point source discharges as well as measuring the efficiency of present and future waste treatment facilities discharging metals to the Liberty Bay system.

Organochlorine Compounds in Surface Sediments

The Liberty Bay surface sediments selected for analysis contained low to nondetectable levels of BHC (benzene hexachloride), Aroclor 1248/Aroclor 1254 (PCBs) polychlorinated biphenyls, and TCP (total identifiable chlorinated pesticides) (Table 5). The concentrations of these compounds measured in the sediment were lower than water-concentrations of related compounds shown to be acutely toxic to Pacific oyster embryos (Woelke, 1972; Cummins, Unpublished Data).

Although there was nothing particularly remarkable about the

Table 5. Concentrations of Several Organochlorine Compounds in Liberty Bay and Clam Bay Surface Sediments.

Station	Concentration ug/g (wet weight)		
	BHC[a]	Aroclor 1248[b]/Aroclor 1254[b]	TCP[c]
Liberty Bay Stations			
S-2	ND[d]	0.004	0.004
WSF-3 (Near Poulsbo STP Outfall)	ND	ND	ND
WSF-5 (Oyster Hatchery Site)	0.004	0.021	0.025
WSF-13 (Keyport STP Outfall)	ND	0.004	0.004
SF-16	ND	0.006	0.006
WS-17 (NTS[e] Paint Shop Storm Sewer Outfall)	ND	ND	ND
Reference Stations			
Clam Bay	ND	0.013	0.013

---

[a] BHC - "Benzene hexachloride"

[b] Polychlorinated biphenyls (PCB's)

[c] TCP (Total identifiable chlorinated pesticides)

[d] ND (Not detected)

[e] NTS Navy Torpedo Station

levels of organochlorine compounds observed, it is of interest to note that surface sediments collected from Station WSF-5 near the Sea Farms hatchery site contained more BHC, Aroclor 1248/Aroclor 1254, and TCPs than any of the other sediments analyzed.

Sulfides in Surface Sediments

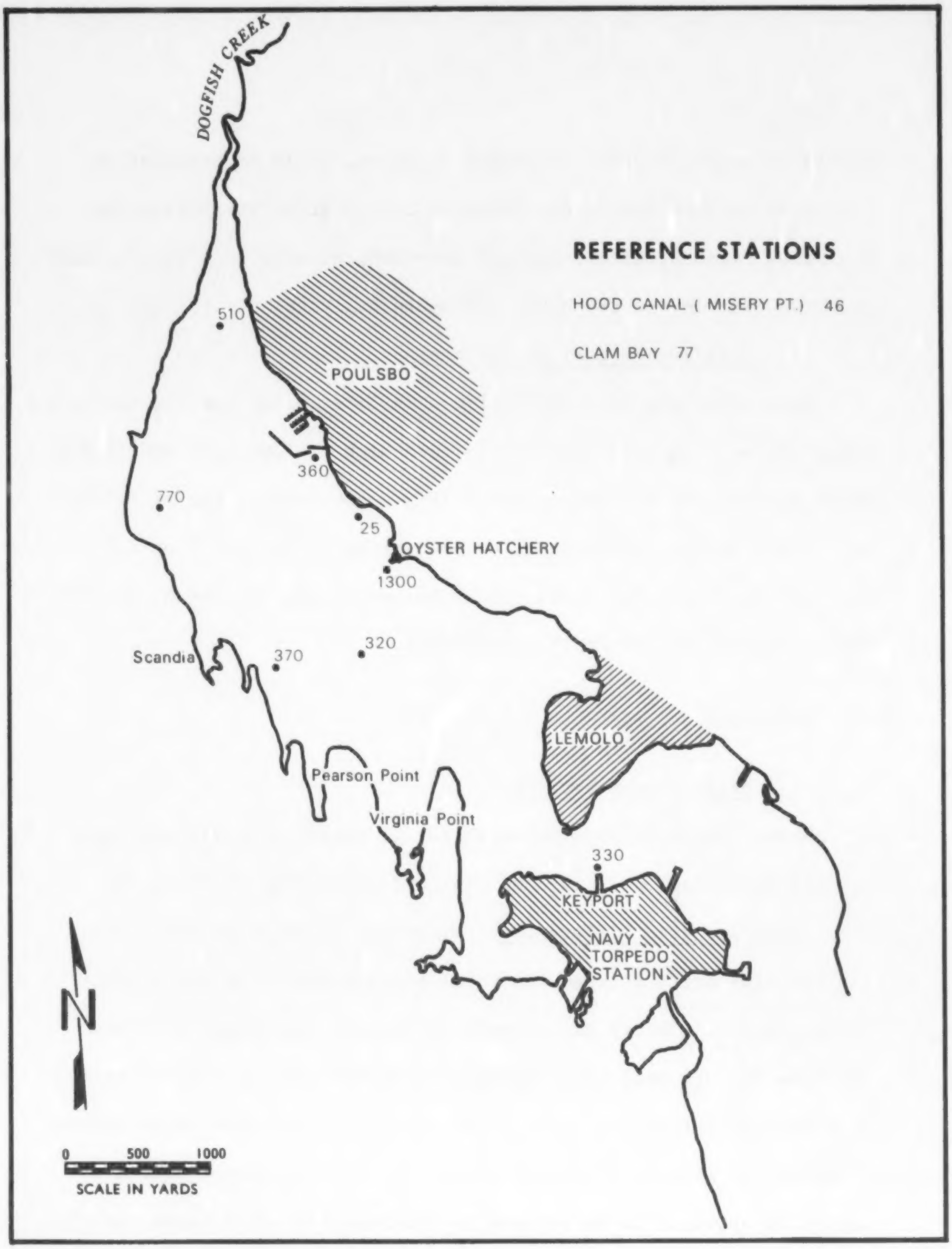
Concentrations of total sulfides in Liberty Bay surface sediments ranged from 25 ug/g at Station S-9 to a high of 1300 ug/g at the Sea Farms hatchery site, Station WSF-5 (Fig. 18). This range of sulfide levels was within the range of concentrations (<10 - 3770 ug/g) reported by O'Neal and Sceva (1971) in sediments from estuarine and marine harbors in the Pacific Northwest.

Shellfish -

Metal Concentrations

Metal concentrations measured in the shellfish collected from Liberty Bay, Clam Bay, and Hood Canal are presented in Table 6.

(Interspecific Differences) With some exceptions, there was a general similarity between the metal concentrations in shellfish collected from Liberty Bay as well as between these shellfish and the Clam Bay and Hood Canal stocks. Although some of the variation in metal concentrations could be attributed to differences in station location, as will be discussed later, the most prominent source of variation appeared to be related to interspecific differences in the metal content of the various species of shellfish analyzed. Metal levels characterizing Japanese and native littleneck clams were quite



DOGFISH CREEK
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) 46
CLAM BAY 77
510
POULSBO
360
770
25
OYSTER HATCHERY
1300
320
Scandia
370
LEMOLO
Pearson Point
Virginia Point
330
KEYPORT
NAVY TORPEDO STATION
N
0 500 1000
SCALE IN YARDS

Figure 18. Total sulfide concentrations in Liberty Bay surface sediments (ug/g dry weight).

TABLE 6. Concentrations of Metals in Shellfish Collected from Liberty Bay, Clam Bay and Hood Canal.

			Concentration µg/g (wet weight)									
Station	Date	Species	Antimony (Sb)	Arsenic (As)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Lead (Pb)	Mercury (Hg)	Nickel (Ni)	Selenium (Se)	Zinc (Zn)
Liberty Bay Stations												
Sf-1 (Upper West Bay)	9-12-75	Pacific Oysters *Crassostrea gigas*	<0.020	0.20	1.1	0.30	7.6	1.4	0.008	2.3	0.040	150
Sf-5 (Oyster Hatchery Site)	9-12-75	Japanese Littleneck Clams *Venerupis japonica*	<0.020	1.0	0.44	0.90	1.9	2.7	0.024	2.7	0.23	19
Sf-6 (West Central Bay)	9-12-75	Japanese Littleneck Clams	<0.030	0.70	0.45	0.80	1.8	1.7	0.023	1.7	0.10	17
	9-12-75	Native Littleneck Clams *Venerupis staminea*	<0.020	1.5	0.50	0.50	1.8	2.0	0.015	1.5	0.19	19
Sf-10 (Southwest Bay)	9-12-75	Japanese Littleneck Clams	<0.020	1.0	0.53	1.6	1.6	1.1	0.024	2.1	0.25	18
	9-12-75	Native Littleneck Clams	<0.030	1.2	0.57	0.70	0.92	1.1	0.019	1.1	0.040	16
Sf-12 (Southeast Bay)	9-12-75	Japanese Littleneck Clams	0.030	1.1	0.35	0.70	1.6	1.2	0.020	1.7	0.070	19
	9-12-75	Native Littleneck Clams	0.020	1.5	0.58	0.70	0.68	1.9	0.012	1.4	0.050	18
Sf-13 (Keyport STP Outfall)	9-12-75	Japanese Littleneck Clams	0.050	0.80	0.38	0.60	1.9	0.96	0.016	1.4	0.050	20
	9-12-75	Native Littleneck Clams	<0.030	1.1	0.45	0.70	1.0	1.1	0.016	2.3	<0.020	25
Sf-14 (Nesika Bay)	9-12-75	Japanese Littleneck Clams	<0.030	0.60	0.43	1.8	1.9	1.1	0.013	2.7	0.16	21
	9-12-75	Native Littleneck Clams	<0.030	1.2	0.47	1.4	1.7	1.2	0.010	15	0.040	17
Sf-15 (Barrage Point)	9-12-75	Native Littleneck Clams	0.020	1.2	0.49	1.0	2.1	1.0	0.012	2.0	0.040	13
	9-12-75	Butter Clams *Saxidomus giganteus*	<0.030	2.2	0.24	1.9	3.8	1.2	0.017	7.8	0.040	18
Reference Stations												
Hood Canal (Misery Point)	9-14-75	Japanese Littleneck Clams	0.040	0.50	0.35	0.70	2.8	1.2	0.013	1.8	0.020	15
Clam Bay	9-14-75	Native Littleneck Clams	<0.030	1.2	0.36	0.90	1.8	1.2	0.013	3.6	0.080	15

similar. Pacific oysters collected from upper Liberty Bay (Station Sf-1), however, contained the highest concentrations of cadmium (1.1 ug/g), copper (7.6 ug/g), and zinc (150 ug/g), while exhibiting the lowest levels of arsenic (0.20 ug/g) and mercury (0.008 ug/g). Marked interspecific differences in trace metal uptake was demonstrated a number of years ago in several species of shellfish taken from New Zealand waters (Brooks and Rumsby, 1965). Interestingly, oysters analyzed during these studies in New Zealand, _Ostrea sinuata_, as well as American oysters, _C. virginica_, collected from Mobile Bay and the Atlantic coast also exhibited high copper and zinc levels relative to the concentrations of other metals present (Shuster and Pringle, 1969; Kopfler and Mayer, 1973). It should be noted, however, that the oysters sampled during the Liberty Bay survey were collected from Coast Oyster Company beds that had been planted some time earlier with oysters grown in other waters. The metal content of these shellfish prior to their transfer to Liberty Bay could have influenced their metal content at the time of our sampling.

Butter clams collected just outside Liberty Bay (Station Sf-15) contained the highest arsenic concentrations (2.2 ug/g) and the second highest levels of copper (3.8 ug/g) and nickel (7.8 ug/g). The highest nickel concentration (15 ug/g) was exhibited by the native littleneck clams collected at Station Sf-14 on Nesika Bay. Japanese littleneck clams collected at the same station exhibited nickel levels of only 2.7 ug/g. The 15 ug/g value appeared to be a possible anomaly because of the uncharacteristic gap between the nickel concentrations of these two species of clams. This high value should not be disregarded, however, without additional confirmation.

(Distribution) The distribution of the various shellfish-associated metal levels throughout the Liberty Bay system is shown in Figures 19-28. Comments about the distribution of these metals within the survey area are based solely on their concentrations in Japanese and native littleneck clams. These species were selected for this "indicator" role because of the broad geographic coverage they provided as well as the apparent similarity in their metal uptake patterns.

Although no pronounced station-associated differences were apparent, clams from Liberty Bay proper tended to exhibit higher concentrations of arsenic, cadmium, lead, mercury, and selenium, while chromium and copper levels tended to be higher in clams collected from stations just outside the Bay. Except for the 15 ug/g nickel concentration measured at Station Sf-14 in Nesika Bay, nickel, antimony and zinc levels remained about the same throughout the Liberty Bay system.

Several of the metals levels measured in Japanese and native littleneck clams appeared to be correlated, to varying degrees, with companion surface sediment metal concentrations. The strongest positive correlation observed in both species involved increasing shellfish and surface sediment lead levels toward the head of the Bay. Comparison of metal levels characterizing shellfish and sediments from Nesika Bay and waters adjacent to the Torpedo Station was not possible because companion samples were not collected in these areas.

(Comparative Data) Metal levels measured in shellfish from Liberty

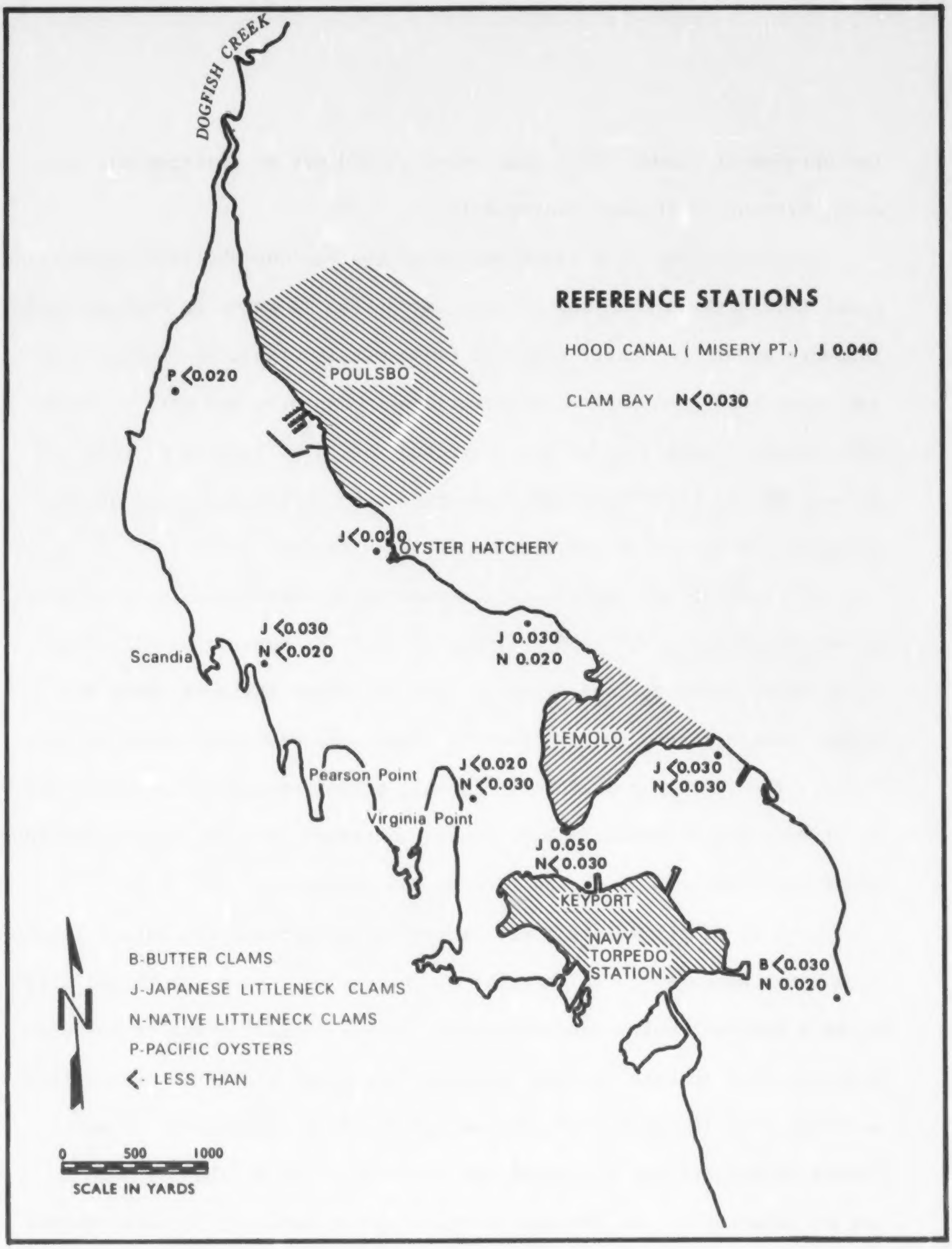

DOGFISH CREEK
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) J 0.040
CLAM BAY N<0.030
P <0.020
POULSBO
J<0.020
OYSTER HATCHERY
J <0.030
N <0.020
Scandia
J 0.030
N 0.020
LEMOLO
Pearson Point
J <0.020
N <0.030
Virginia Point
J <0.030
N <0.030
J 0.050
N< 0.030
KEYPORT
NAVY
TORPEDO
STATION
B <0.030
N 0.020
N
B-BUTTER CLAMS
J-JAPANESE LITTLENECK CLAMS
N-NATIVE LITTLENECK CLAMS
P-PACIFIC OYSTERS
<- LESS THAN
0
500
1000
SCALE IN YARDS

Figure 19. Antimony concentrations in several species of Liberty Bay shellfish (ug/g wet weight).

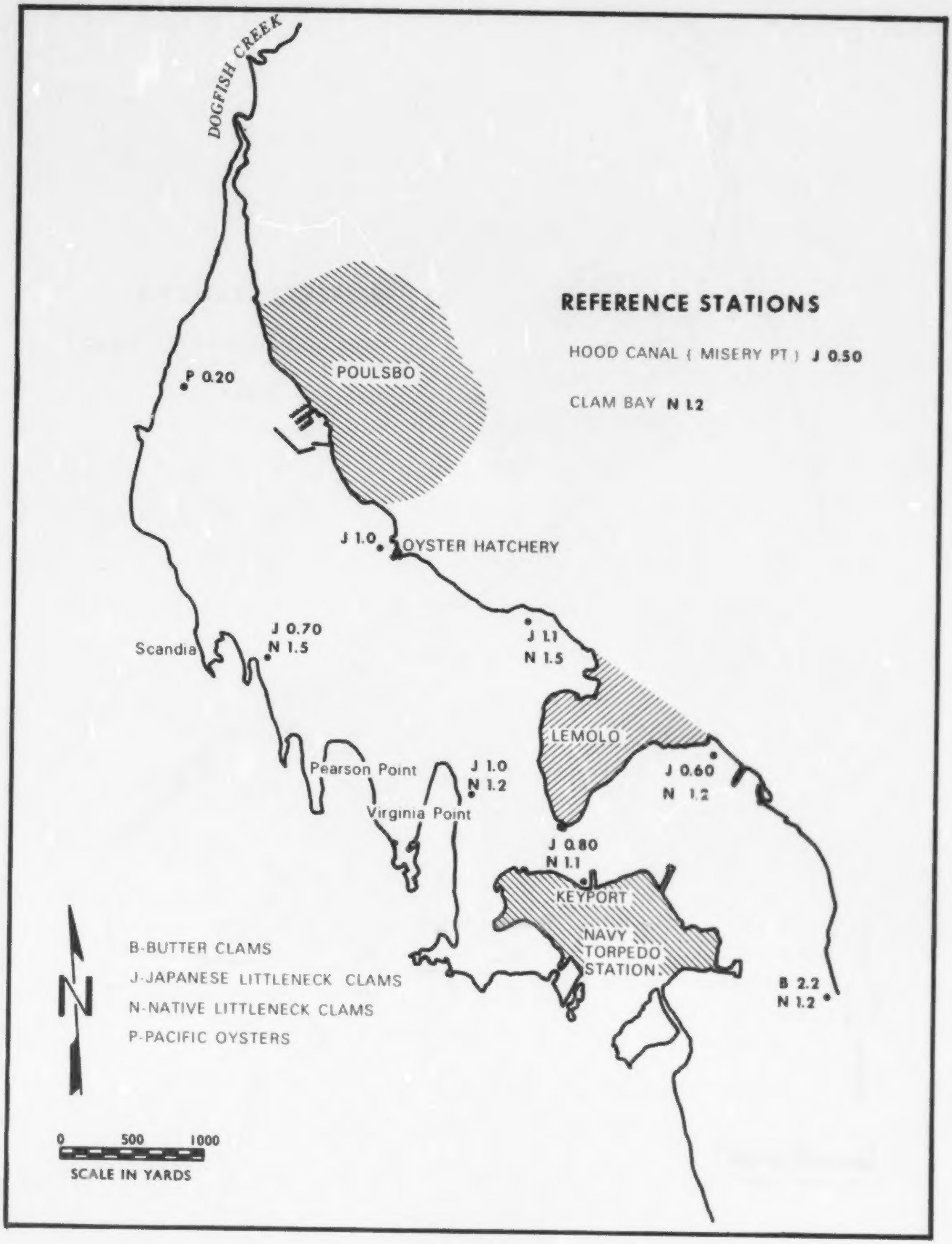

DOGFISH CREEK
REFERENCE STATIONS
HOOD CANAL (MISERY PT) J 0.50
CLAM BAY N 1.2
POULSBO
P 0.20
J 1.0
OYSTER HATCHERY
J 0.70
N 1.5
Scandia
J 1.1
N 1.5
LEMOLO
J 0.60
N 1.2
Pearson Point
J 1.0
N 1.2
Virginia Point
J 0.80
N 1.1
KEYPORT
NAVY
TORPEDO
STATION
B 2.2
N 1.2
B-BUTTER CLAMS
J-JAPANESE LITTLENECK CLAMS
N-NATIVE LITTLENECK CLAMS
P-PACIFIC OYSTERS
N
0
500
1000
SCALE IN YARDS

Figure 20. Arsenic concentrations in several species of Liberty Bay shellfish (ug/g wet weight).

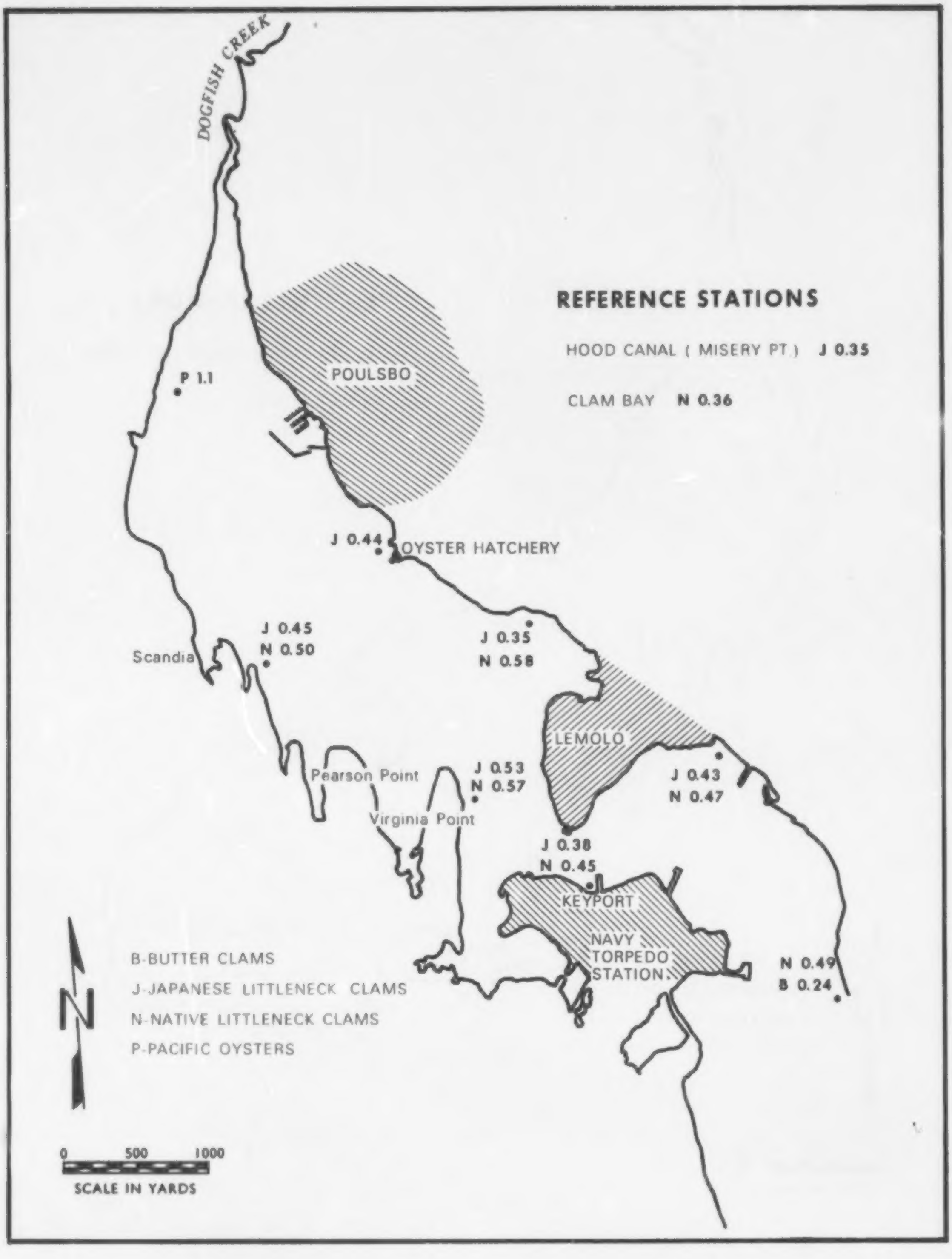

DOGFISH CREEK
REFERENCE STATIONS
HOOD CANAL (MISERY PT) J 0.35
CLAM BAY N 0.36
P 1.1
POULSBO
J 0.44
OYSTER HATCHERY
J 0.45
N 0.50
Scandia
J 0.35
N 0.58
LEMOLO
Pearson Point
J 0.53
N 0.57
Virginia Point
J 0.43
N 0.47
J 0.38
N 0.45
KEYPORT
NAVY TORPEDO STATION
N 0.49
B 0.24
N
B-BUTTER CLAMS
J-JAPANESE LITTLENECK CLAMS
N-NATIVE LITTLENECK CLAMS
P-PACIFIC OYSTERS
0
500
1000
SCALE IN YARDS

Figure 21. Cadmium concentrations in several species of Liberty Bay shellfish (ug/g wet weight).

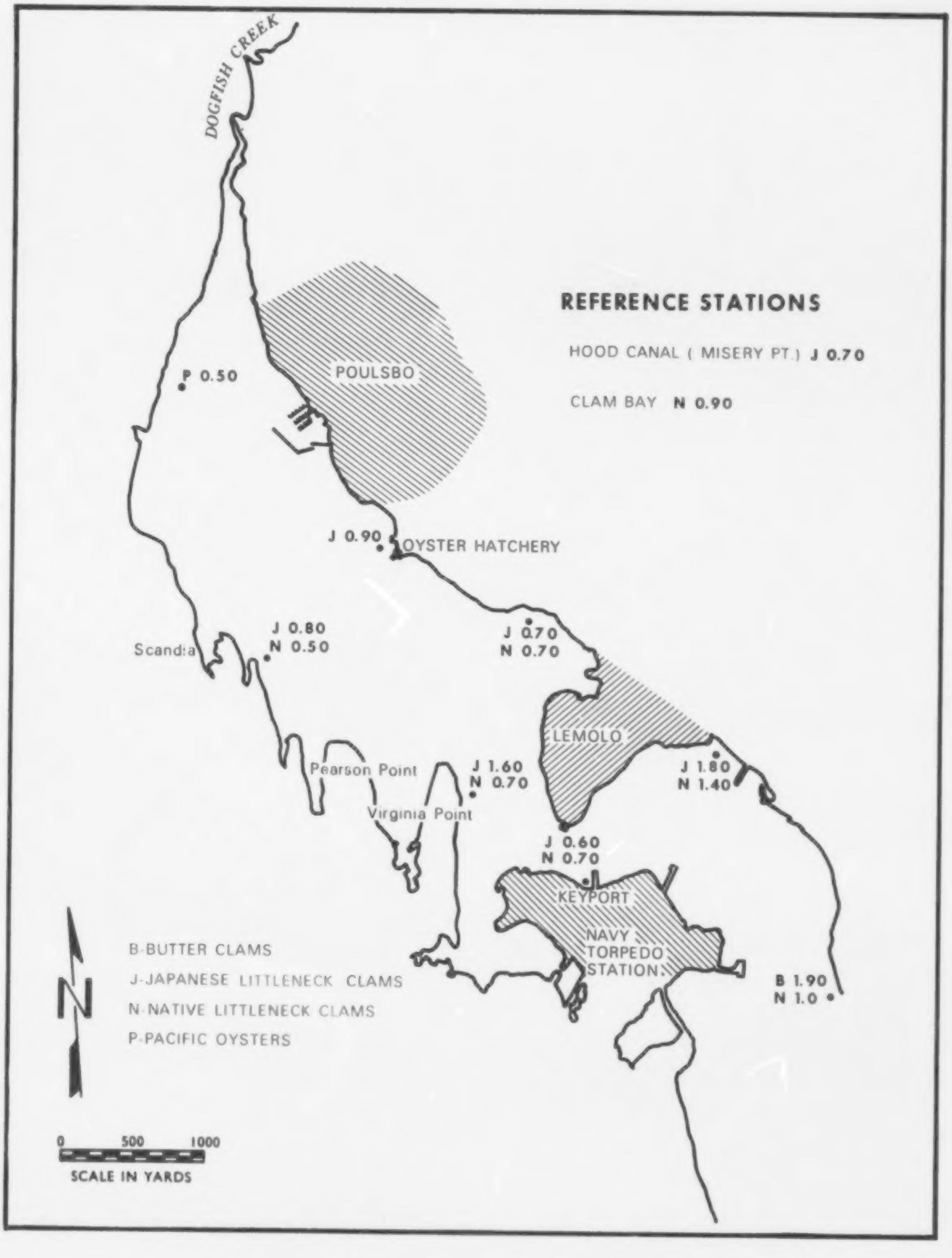

DOGFISH CREEK
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) J 0.70
CLAM BAY N 0.90
POULSBO
P 0.50
J 0.90
OYSTER HATCHERY
J 0.80
N 0.50
Scandia
J 0.70
N 0.70
LEMOLO
Pearson Point
J 1.60
N 0.70
Virginia Point
J 1.80
N 1.40
J 0.60
N 0.70
KEYPORT
NAVY TORPEDO STATION
B 1.90
N 1.0
B-BUTTER CLAMS
J-JAPANESE LITTLENECK CLAMS
N-NATIVE LITTLENECK CLAMS
P-PACIFIC OYSTERS
N
0
500
1000
SCALE IN YARDS

Figure 22. Chromium concentrations in several species of Liberty Bay shellfish (ug/g wet weight).

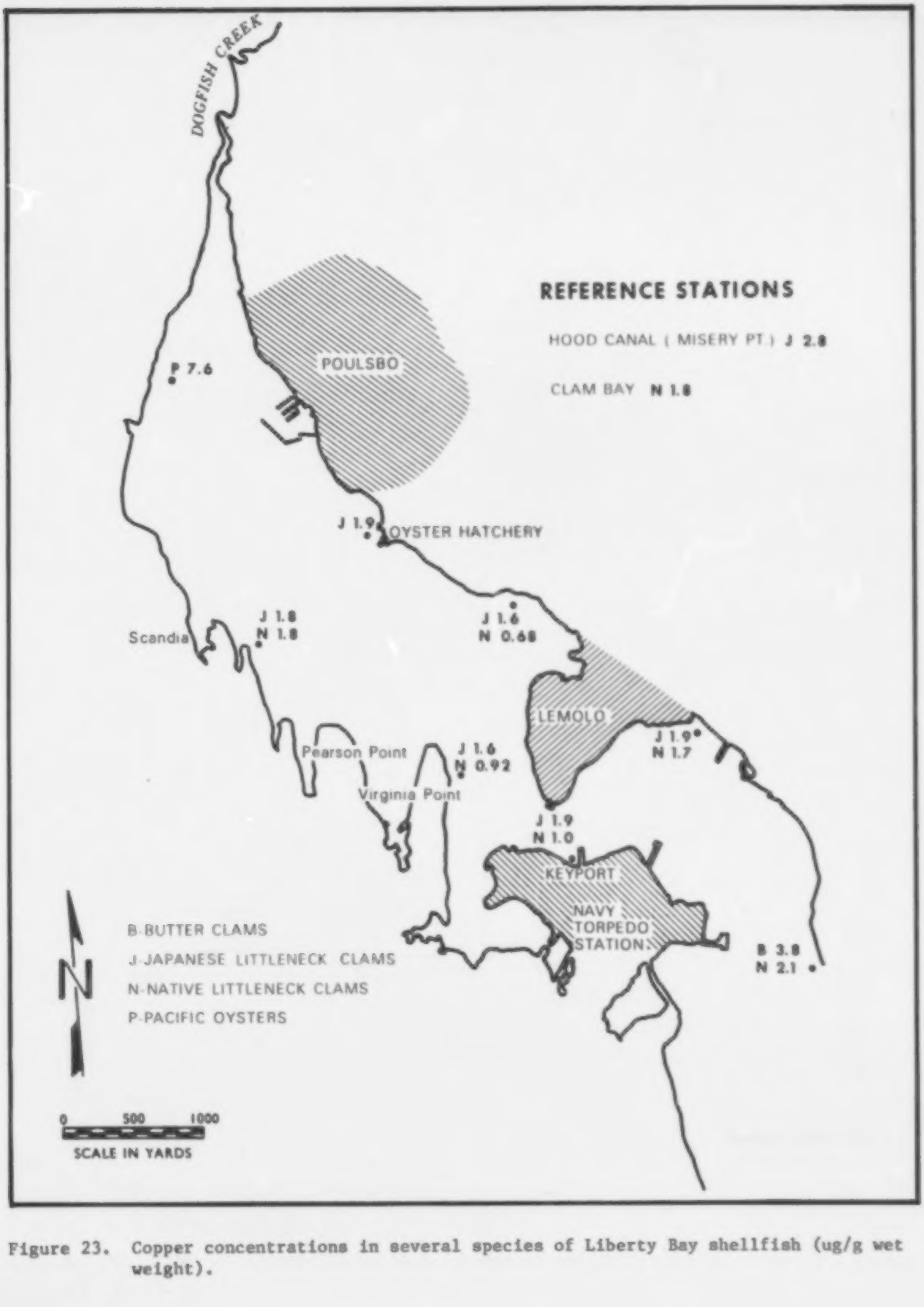

DOGFISH CREEK
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) J 2.8
CLAM BAY N 1.8
P 7.6
POULSBO
J 1.9
OYSTER HATCHERY
J 1.8
N 1.8
Scandia
J 1.6
N 0.68
LEMOLO
J 1.9
N 1.7
Pearson Point
J 1.6
N 0.92
Virginia Point
J 1.9
N 1.0
KEYPORT
NAVY
TORPEDO
STATION
B 3.8
N 2.1
B-BUTTER CLAMS
J-JAPANESE LITTLENECK CLAMS
N-NATIVE LITTLENECK CLAMS
P-PACIFIC OYSTERS
N
0
500
1000
SCALE IN YARDS

Figure 23. Copper concentrations in several species of Liberty Bay shellfish (ug/g wet weight).

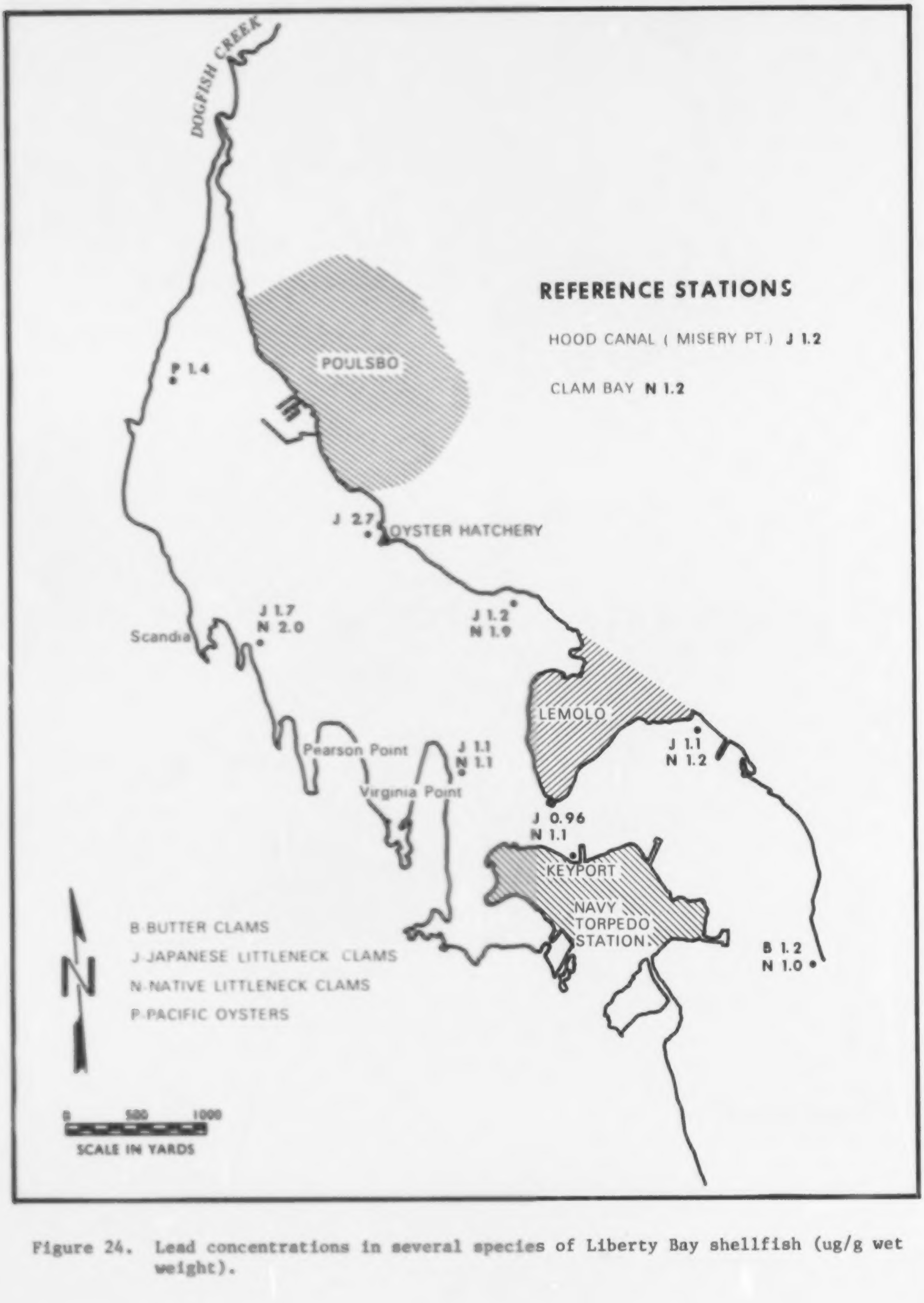

DOGFISH CREEK
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) J 1.2
CLAM BAY N 1.2
POULSBO
P 1.4
J 2.7
OYSTER HATCHERY
J 1.7
N 2.0
Scandia
J 1.2
N 1.9
LEMOLO
Pearson Point
J 1.1
N 1.1
Virginia Point
J 1.1
N 1.2
J 0.96
N 1.1
KEYPORT
NAVY TORPEDO STATION
B 1.2
N 1.0
B-BUTTER CLAMS
J-JAPANESE LITTLENECK CLAMS
N-NATIVE LITTLENECK CLAMS
P-PACIFIC OYSTERS
N
0
500
1000
SCALE IN YARDS

Figure 24. Lead concentrations in several species of Liberty Bay shellfish (ug/g wet weight).

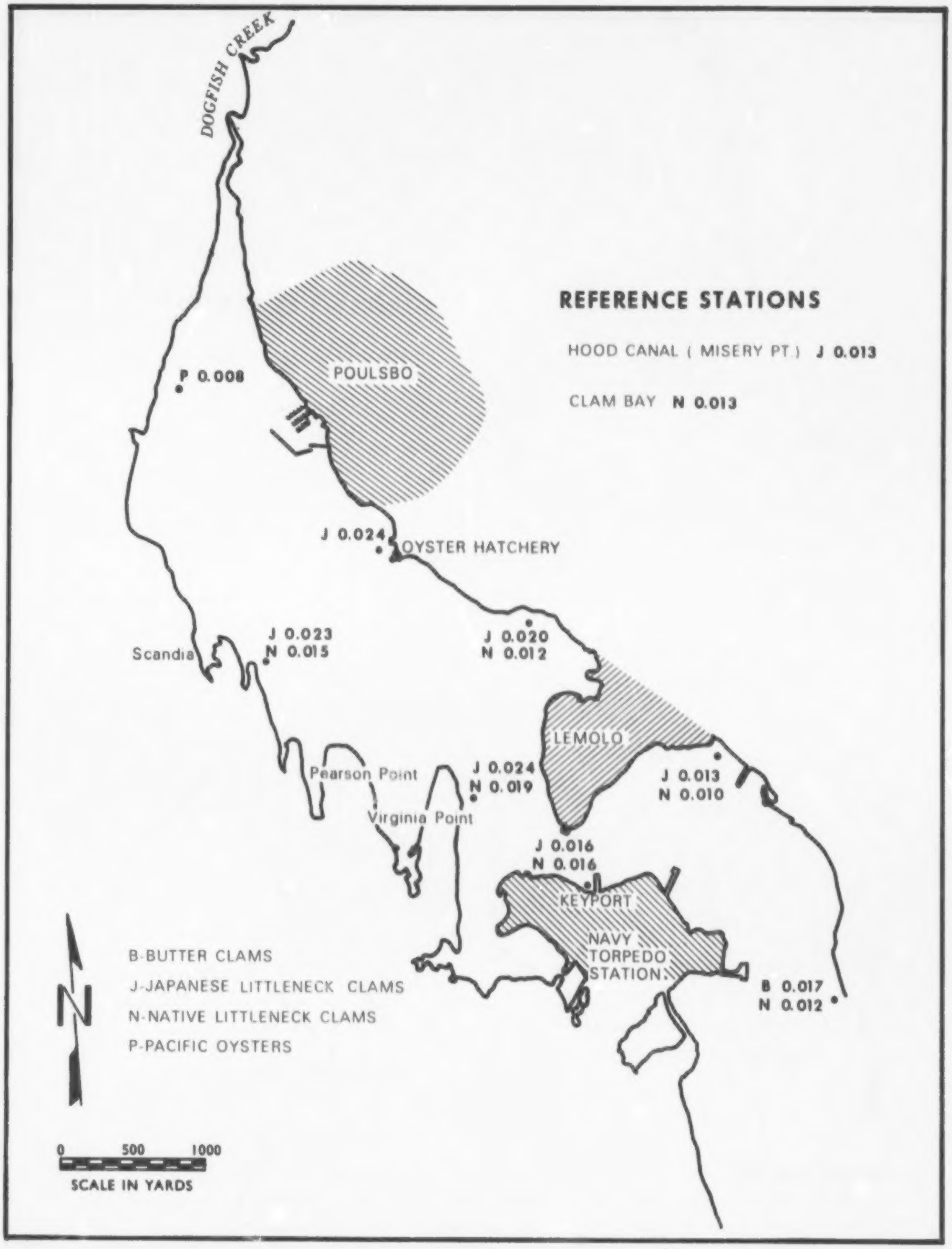

DOGFISH CREEK
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) J 0.013
CLAM BAY N 0.013
POULSBO
P 0.008
J 0.024 OYSTER HATCHERY
J 0.023
N 0.015
Scandia
J 0.020
N 0.012
LEMOLO
Pearson Point
J 0.024
N 0.019
Virginia Point
J 0.013
N 0.010
J 0.016
N 0.016
KEYPORT
NAVY TORPEDO STATION
B 0.017
N 0.012
B-BUTTER CLAMS
J-JAPANESE LITTLENECK CLAMS
N-NATIVE LITTLENECK CLAMS
P-PACIFIC OYSTERS
N
0
500
1000
SCALE IN YARDS

Figure 25. Mercury concentrations in several species of Liberty Bay shellfish (ug/g wet weight).

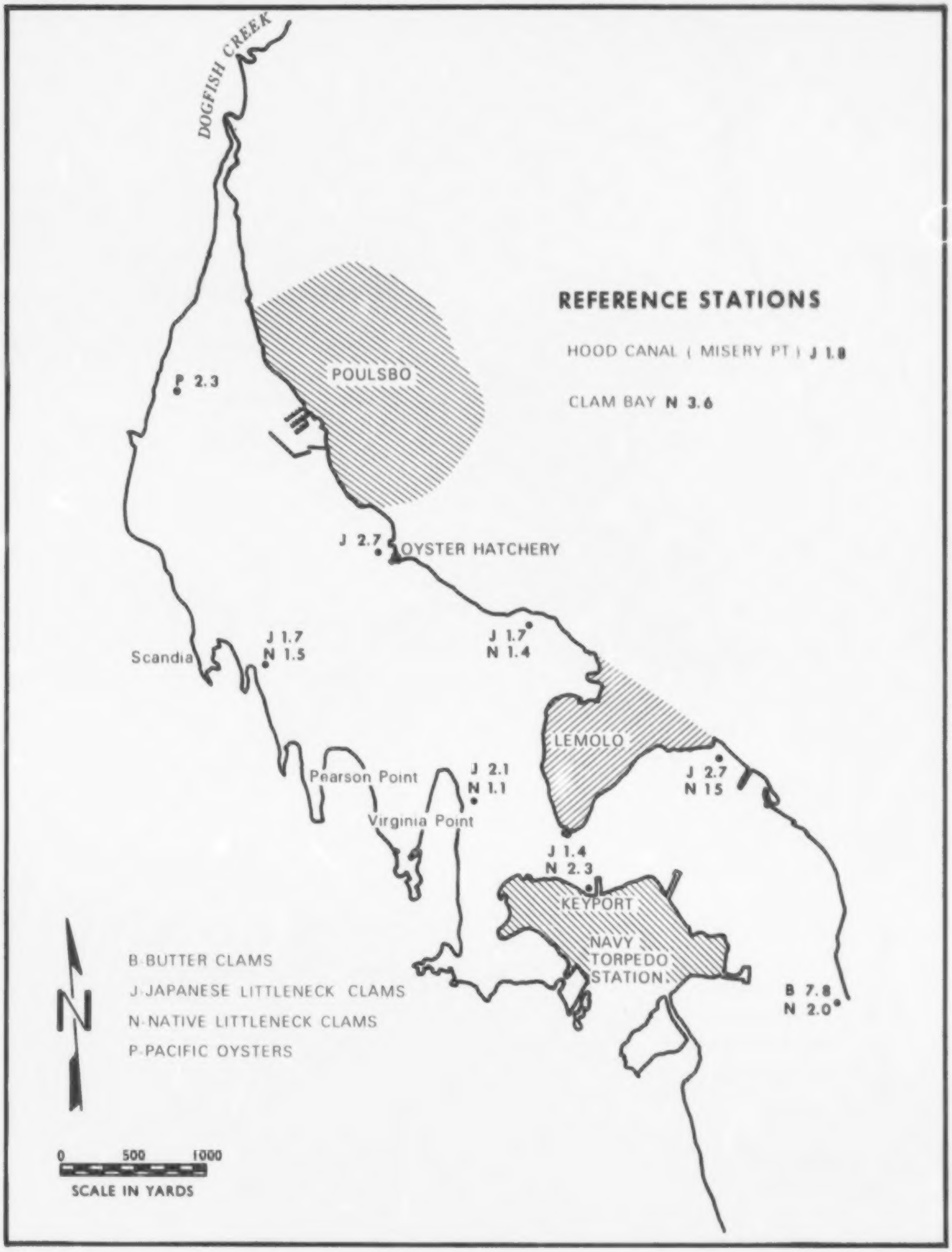

DOGFISH CREEK
REFERENCE STATIONS
HOOD CANAL (MISERY PT) J 1.8
CLAM BAY N 3.6
P 2.3
POULSBO
J 2.7
OYSTER HATCHERY
Scandia
J 1.7
N 1.5
J 1.7
N 1.4
LEMOLO
Pearson Point
J 2.1
N 1.1
J 2.7
N 15
Virginia Point
J 1.4
N 2.3
KEYPORT
NAVY
TORPEDO
STATION
B BUTTER CLAMS
J JAPANESE LITTLENECK CLAMS
N NATIVE LITTLENECK CLAMS
P PACIFIC OYSTERS
B 7.8
N 2.0
N
0
500
1000
SCALE IN YARDS

Figure 26. Nickel concentrations in several species of Liberty Bay shellfish (ug/g wet weight).

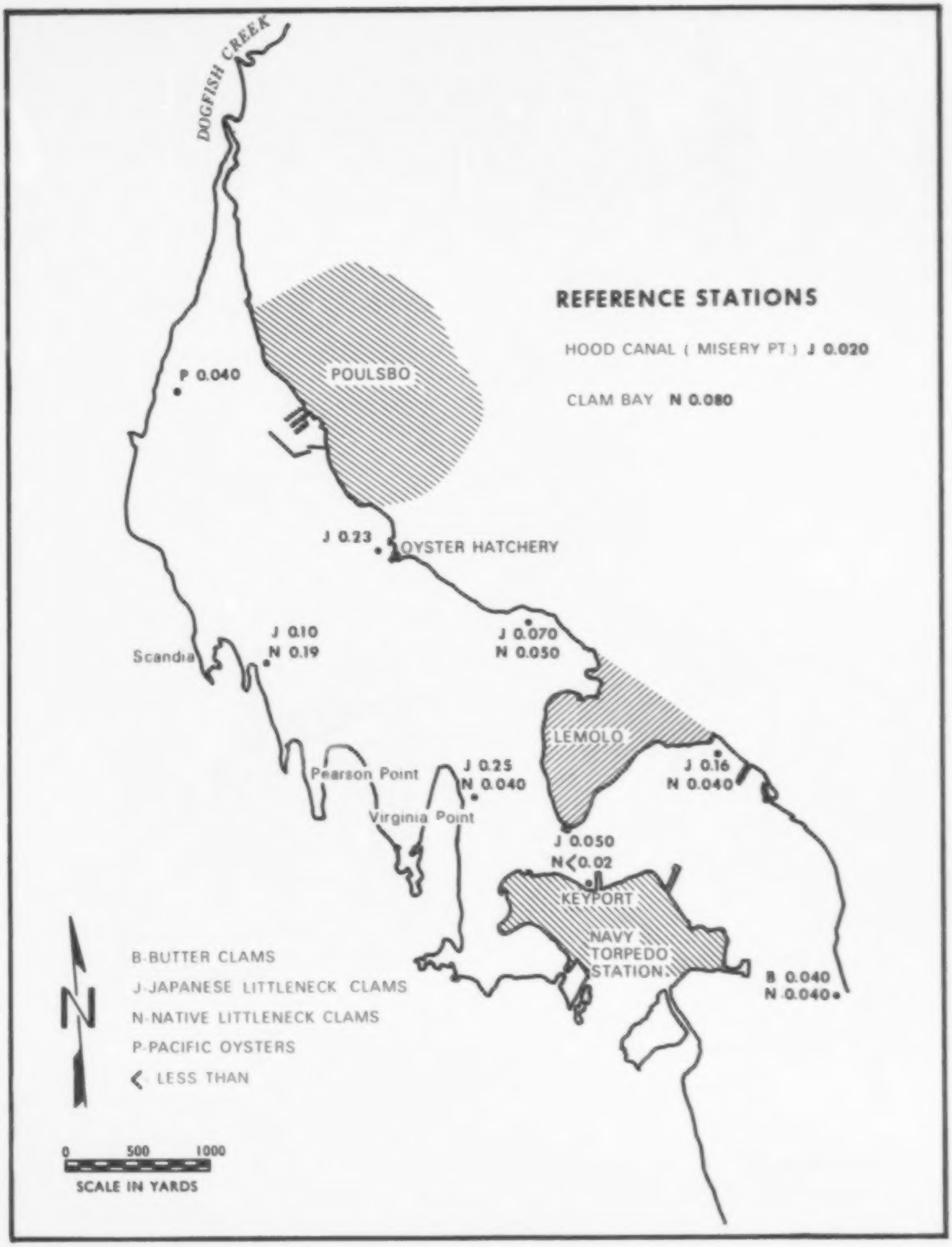

DOGFISH CREEK
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) J 0.020
CLAM BAY N 0.080
P 0.040
POULSBO
J 0.23
OYSTER HATCHERY
J 0.10
N 0.19
Scandia
J 0.070
N 0.050
LEMOLO
J 0.16
N 0.040
Pearson Point
J 0.25
N 0.040
Virginia Point
J 0.050
N<0.02
KEYPORT
NAVY
TORPEDO
STATION
B 0.040
N 0.040
B-BUTTER CLAMS
J-JAPANESE LITTLENECK CLAMS
N-NATIVE LITTLENECK CLAMS
P-PACIFIC OYSTERS
< LESS THAN
N
0
500
1000
SCALE IN YARDS

Figure 27. Selenium concentrations in several species of Liberty Bay shellfish (ug/g wet weight).

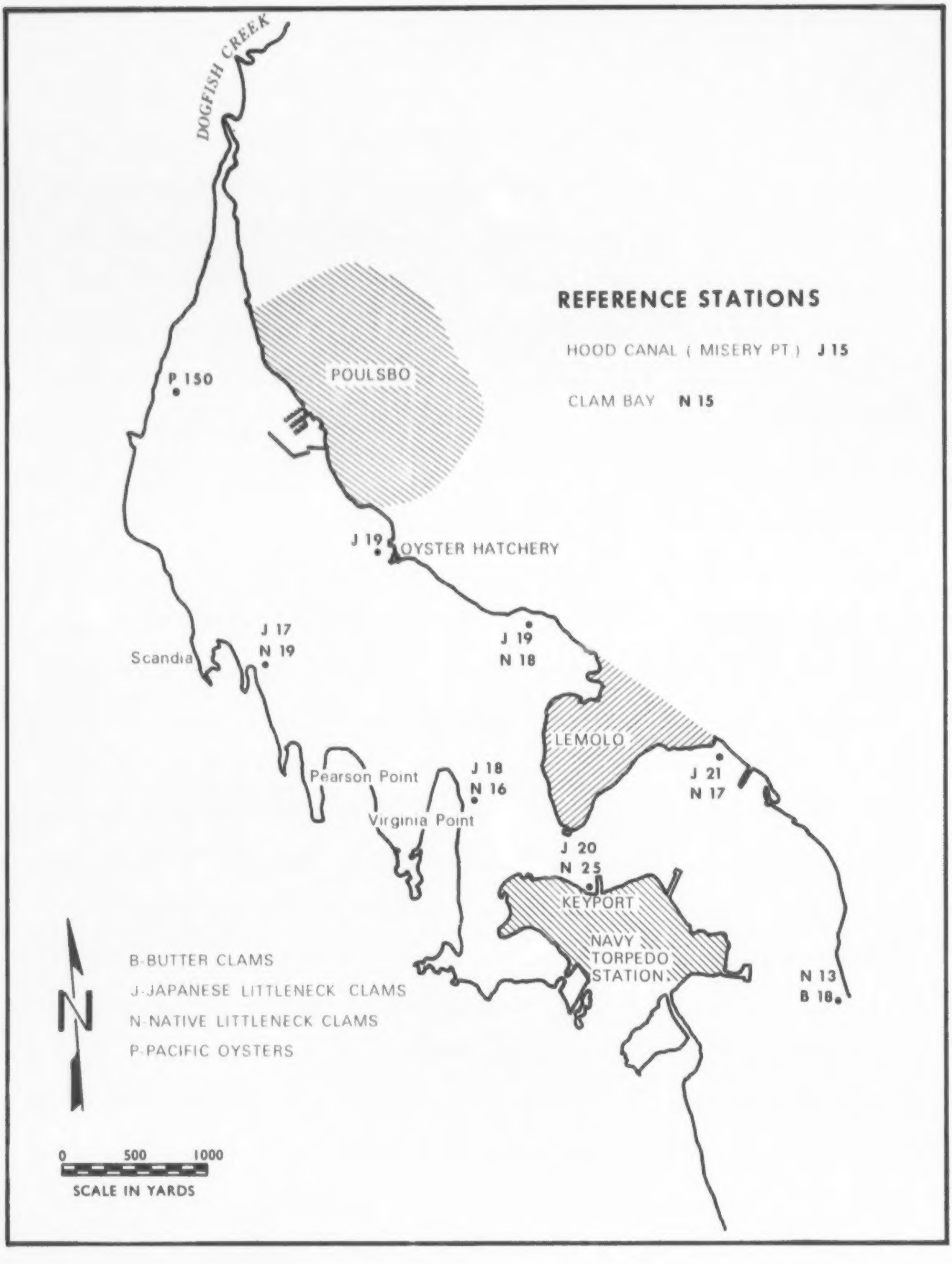

DOGFISH CREEK
REFERENCE STATIONS
HOOD CANAL (MISERY PT) J 15
CLAM BAY N 15
POULSBO
P 150
J 19
OYSTER HATCHERY
J 17
N 19
Scandia
J 19
N 18
LEMOLO
J 21
N 17
Pearson Point
J 18
N 16
Virginia Point
J 20
N 25
KEYPORT
NAVY
TORPEDO
STATION
N 13
B 18
B-BUTTER CLAMS
J-JAPANESE LITTLENECK CLAMS
N-NATIVE LITTLENECK CLAMS
P-PACIFIC OYSTERS
N
0
500
1000
SCALE IN YARDS

Figure 28. Zinc concentrations in several species of Liberty Bay shellfish (ug/g wet weight).

Bay, Clam Bay, and Hood Canal by the various state and federal agencies that responded to the Sea Farms report of high mercury concentrations in Liberty Bay waters are presented in Tables 7 to 10. Included in these tables are the data provided by FDA showing the range of metal levels in shellfish collected in 1970 and 1971 from various "open" and "closed" shellfish growing areas along the west coast. The "open" or "closed" classification of these areas was based on State evaluations of the actual or potential bacteriological quality of the water (Personal Communication, James Davis, U.S. FDA, Seattle, WA).

In addition to the reasonable agreement between the results of the various laboratories, one of the most distinctive features of these data was the relationship between metals in shellfish from the Liberty Bay system compared to levels in shellfish from the other areas. The average concentrations of arsenic, cadmium, lead, and nickel measured by EPA in all species collected from the Liberty Bay system exceeded the average concentrations of these metals in the same species from other west coast waters as well as from Clam Bay and Hood Canal. Average Liberty Bay copper concentrations were less than the average levels of copper in shellfish from the other areas, while average Liberty Bay mercury concentrations were greater than the Clam Bay and Hood Canal values, but less than the west coast average. The relation of Liberty Bay zinc and copper levels to the levels measured in shellfish from the other areas was not as well defined. In most cases, however, the average concentrations of the metals in Liberty Bay shellfish were greater than or equal to the average levels measured in shellfish collected elsewhere.

TABLE 7. Concentrations of Metals in Japanese Littleneck Clams, *Venerupis japonica*, from Liberty Bay, Hood Canal, and Other West Coast Locations[a].

Element	West Coast FDA Mean (Range)[b]	Liberty Bay EPA Mean (Range)[c]	Liberty Bay FDA Mean (Range)[d]	Liberty Bay DSHS[e]	Hood Canal EPA Reference Station[c]
			Concentration µg/g (wet weight)		
Antimony (Sb)	---	<0.030 (<0.020-0.050)	---	---	0.040
Arsenic (As)	0.10 (0.0-0.42)	0.87 (0.60-1.1)	---	---	0.50
Cadmium (Cd)	0.30 (0.020-0.53)	0.43 (0.35-0.53)	0.15 (0.13-0.16)	0.36	0.35
Chromium (Cr)	1.1 (0.0-3.2)	1.1 (0.60-1.8)	0.45 (0.38-0.52)	0.25	0.70
Copper (Cu)	2.3 (0.78-7.6)	1.8 (1.6-1.9)	2.5 (2.5-2.6)	2.0	2.8
Lead (Pb)	0.45 (0.0-1.2)	1.5 (0.96-2.7)	ND	0.20	1.2
Mercury (Hg)	0.16 (0.050-0.78)	0.020 (0.013-0.024)	0.025 (0.02-0.03)	0.02	0.013
Nickel (Ni)	2.0 (1.0-2.9)	2.1 (1.4-2.7)	---	2.3	1.8
Selenium (Se)	---	0.14 (0.050-0.25)	---	---	0.020
Zinc (Zn)	14 (8.7-20)	19 (17-21)	13 (10-15)	14	15

---

[a] Values reduced to two significant figures where appropriate.

[b] U.S. Food and Drug Administration, "Table of Analytical Values for Heavy Metals in Shellfish Taken From Various West Coast Estuaries in 1970-71."

[c] U.S. Environmental Protection Agency. Collected 9/12-14/75.

[d] U.S. Food and Drug Administration. Collected 9/22/75, Nesika Bay.

[e] Washington State Department of Social and Health Services. Collected 9/22/75, Nesika Bay.

ND Not detected.

Table 8. Concentrations of Metals in Native Littleneck Clams, *Venerupis staminea*, from Liberty Bay, Clam Bay, and Other West Coast Locations.[a]

Element	West Coast FDA Mean (Range)[b]	Liberty Bay EPA Mean (Range)[c]	Liberty Bay DSHS[d]	Clam Bay EPA Reference Station[c]
		Concentration µg/g (wet weight)		
Antimony (Sb)	---	<0.025 (<0.020-0.030)	---	<0.030
Arsenic (As)	0.08 (0-0.25)	1.3 (1.1-1.5)	---	1.2
Cadmium (Cd)	0.29 (0.09-0.54)	0.51 (0.45-0.58	0.36	0.36
Chromium (Cr)	1.1 (0-2.3)	0.83 (0.50-1.4)	0.28	0.90
Copper (Cu)	2.0 (0.9-4.6)	1.4 (0.68-2.1)	1.4	1.8
Lead (Pb)	0.22 (0-1.1)	1.4 (1.0-2.0)	0.24	1.2
Mercury (Hg)	0.05 (0-0.12)	0.014 (0.010-0.019)	0.04	0.013
Nickel (Ni)	1.2 (0.38-1.9)	3.9 (1.1-15)	1.92	3.6
Selenium (Se)	---	<0.63 (<0.020-0.19)	---	0.080
Zinc (Zn)	26 (12-160)	18 (13-25)	12	15

---

[a] Values reduced to two significant figures where appropriate.

[b] U.S. Food and Drug Administration, "Table of Analytical Values for Heavy Metals in Shellfish Taken From Various West Coast Estuaries in 1970-71."

[c] U.S. Environmental Protection Agency. Collected 9/12-14/75.

[d] Washington State Department of Social and Health Services. Collected 9/23/75, southwest Bay.

TABLE 9. Concentrations of Metals in Butter Clams, *Saxidomus giganteus*, from Liberty Bay and Other West Coast Locations.[a]

Element	West Coast FDA Mean (Range)[b]	Liberty Bay EPA[c]
	Concentration µg/g (wet weight)	
Antimony (Sb)	---	<0.03
Arsenic (As)	0.36 (0-0.87)	2.2
Cadmium (Cd)	0.05 (0-0.14)	0.24
Chromium (Cr)	1.6 (0.33-3.7)	1.9
Copper (Cu)	6.3 (3.7-8.2)	3.8
Lead (Pb)	0.29 (0-1.3)	1.2
Mercury (Hg)	0.30 (0.086-0.60)	0.017
Nickel (Ni)	1.5 (0.23-2.7)	7.8
Selenium (Se)	---	0.04
Zinc (Zn)	15 (10-16)	18

---

[a] Values reduced to two significant figures where appropriate.

[b] U.S. Food and Drug Administration, "Table of Analytical Values for Heavy Metals in Shellfish Taken From Various West Coast Estuaries in 1970-71."

[c] U.S. Environmental Protection Agency. Collected 9/12/75.

Table 10. Concentrations of Metals in Pacific Oysters, *Crassostrea gigas*, from Liberty Bay and Other West Coast Locations[a].

Element	West Coast FDA Mean (Range)[b]	Liberty Bay EPA[c]	Liberty Bay FDA Mean (Range)[d]	Liberty Bay DSHS Mean (Range)[e]	Liberty Bay NMFS Mean (Range)[f]
			Concentration µg/g (wet weight)		
Antimony (Sb)	---	<0.020	---	---	---
Arsenic (As)	0.06 (0-0.23)	0.20	---	---	---
Cadmium (Cd)	0.94 (0.53-1.7)	1.1	1.0 ---	1.3 (1.2-1.5)	---
Chromium (Cr)	0.32 (0-1.3)	0.50	0.25 (0.23-0.27)	0.27 (0.25-0.28)	---
Copper (Cu)	20 (6.4-50)	7.6	1.1 (0.97-1.3)	15 (12-17)	---
Lead (Pb)	0.32 (0-2.0)	1.4	<0.18 (ND-0.18)	0.22 ---	---
Mercury (Hg)	0.05 (0-0.12)	0.008	0.015 (0.010-0.020)	0.02 1.01-0.04)	0.03 (0.02-0.04)
Nickel (Ni)	0.78 (0-1.8)	2.3	---	1.8 (1.5-2.0)	---
Selenium (Se)	---	0.040	---	---	---
Zinc (Zn)	150 (66-300)	150	160 (140-170)	200 (170-230)	---

---

[a] Values reduced to two significant figures where appropriate.

[b] U.S. Food and Drug Administration, "Table of Analytical Values for Heavy Metals in Shellfish Taken from Various West Coast Estuaries in 1970-71."

[c] U.S. Environmental Protection Agency. Collected 9/12/75.

[d] U.S. Food and Drug Administration. Collected 9/23/75, central and upper Bay.

[e] Washington State Department of Social and Health Services. Collected 9/23/75, central and upper Bay.

[f] National Marine Fisheries Service. Pacific Utilization Research Center. Collected 8/15/75, Sea Farms site.

ND Not detected.

The slightly elevated nature of many of the metal concentrations characterizing Liberty Bay shellfish tended to confirm the historical fact that metallic wastes have been discharged to the system for many years. However, the general similarity between the metal levels in shellfish from Liberty Bay, Hood Canal, Manchester, and other west coast areas suggested that, from the standpoint of trace metal uptake, metallic discharges to the Liberty Bay system had not seriously impacted the shellfish populations sampled. Significantly, the levels of mercury measured in shellfish from Liberty Bay (0.008 - 0.024 ug/g) as well as from the Clam Bay and Hood Canal reference stations (0.013 ug/g) were well below the proposed Food and Drug Administration (FDA) action level of 0.5 ug/g (wet weight) for mercury in fish and shellfish (U.S. FDA, 1974). These shellfish would, therefore, have been considered safe for human consumption from the standpoint of their mercury content. Their relatively low mercury content also suggested that it was unlikely that large continuous or intermittent discharges of mercury had been made to the Liberty Bay system over an extended period. This becomes particularly evident when considering the ability of fish and shellfish to exhibit mercury levels that are hundreds or thousands of times greater than the mercury concentrations of the waters in which they are living (Peakall and Lovett, 1972).

Organochlorine Concentrations

The levels of polychlorinated biphenyls (PCBs) measured in shellfish from Liberty Bay are presented in Table 11.

Table 11. Concentrations of Polychlorinated Biphenyls in Shellfish Collected from Liberty Bay.

Station	Species	Concentration ng/g (wet weight) Aroclor 1242	Aroclor 1248/1254	Total
Sf-1 (Upper West Bay)	Pacific Oysters *Crassostrea gigas*	<10	<20	<20
Sf-5 (Oyster Hatchery Site)	Japanese Littleneck Clams *Venerupis japonica*	<10	<20	<20
Sf-10 (Southwest Bay)	Japanese Littleneck Clams	46	46	92

Total PCB concentrations (Aroclor 1242 plus Aroclor 1248 and 1254) measured in Liberty Bay shellfish ranged from <20 ng/g at Stations Sf-1 and Sf-5 to 92 ng/g at Station Sf-10.

The total PCB concentration measured in Japanese Littleneck Clams from Station Sf-10 (92 ng/g) was higher than the levels of PCBs (Aroclor 1254 and Aroclor 1260) measured by Claeys and coworkers (1975) in cockles, *Clinocardium nuttallii*, and Eastern softshell clams, *Mya arenaria*, from several Oregon estuaries. Although this determinate level was believed to reflect limited inputs of PCBs to the Liberty Bay system, it was considerably lower than the PCB concentrations (390 - 1170 ng/g) measured in Asiatic clams, *Corbicula fluminea*, from the Columbia River estuary (Claeys *et al*., 1975).

Fish Muscle Tissue -

Metal Concentrations

Presented in Table 12 are the concentrations of metals measured in the muscle tissues of various bottom fishes collected during the survey. Unlike the oysters and clams, the fishes sampled from the Liberty Bay system were free to move throughout the system as well as into neighboring Puget Sound waters. The metal concentrations in their tissues were considered, therefore, to primarily reflect conditions throughout this range rather than at any one station.

Few differences were observed in the concentrations of the various metals measured in the fishes from Liberty Bay, regardless of species or collection site. The metal concentrations in the muscle tissues of these fishes were also similar to levels measured in the fishes from the Hood Canal and Clam Bay reference stations and generally corresponded to levels measured in fishes from central Puget Sound (Huntamer and Schell, 1974). The only major difference involved the 14 ug/g arsenic concentration measured in the Clam Bay rock sole compared to the relatively low range of arsenic levels (0.10 - 0.70 ug/g) found in the other fishes collected. This dissimilarity was not attributable to interspecific differences or variations in size since the sample population exhibiting the low arsenic levels contained rock sole of comparable size. The relatively high arsenic value did correspond, however, to the range of levels (5.4 - 13.8 ug/g) reported by Huntamer and Schell (1974) in the muscle tissues of flat fishes from Colvos Passage and Commencement Bay. Although the high arsenic level (14 ug/g) may have

Table 12. Concentrations of Metals in the Muscle Tissue of Bottom Fishes Collected from Liberty Bay, Clam Bay, and Hood Canal.

Station	Date	Species	Length (cm)	Concentration µg/g (wet weight)											
				Antimony (Sb)	Arsenic (As)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Manganese (Mn)	Mercury (Hg)	Nickel (Ni)	Selenium (Se)	Zinc (Zn)
Liberty Bay Stations															
WSF-3 (Near Poulsbo STP Outfall)	9-15-75	Great Sculpin *Myoxocephalus polyacanthocephalus*	28	<0.020	<0.10	0.10	0.50	0.40	6.0	<1.0	0.20	0.047	2.0	0.040	8.2
WSF-5 (Oyster Hatchery Site)	9-17-75	Buffalo Sculpin *Enophrys bison*	25	<0.020	<0.10	0.10	0.40	0.47	10	<1.0	0.30	0.047	7.9	<0.030	17
WSF-13 (Keyport STP Outfall)	9-15-75	C - O Sole *Pleuronichthys coenosus*	30	<0.020	0.20	0.10	0.30	0.29	3.9	<1.0	<0.20	0.15	1.5	<0.020	6.0
SF-16 (NTS[a] STP Outfall)	9-17-75	Rock Sole *Lepidopsetta bilineata*	30	0.020	0.70	0.10	0.40	0.29	4.8	<1.0	0.60	0.066	1.0	0.080	6.9
	9-17-75	Rock Sole *Lepidopsetta bilineata*	20	0.050	0.10	0.10	0.40	0.39	4.8	<1.0	0.40	0.036	1.9	0.050	7.7
WSF-19 (Near Plating Plant Overflow Outfall)	9-17-75	Rock Sole *L. bilineata*	30	0.020	0.70	0.10	0.40	0.56	4.2	<1.0	0.20	0.054	7.9	0.090	7.6
	9-17-75	Great Sculpin *M. polyacanthocephalus*	30	0.040	<0.10	0.10	0.40	0.46	7.4	<1.0	0.40	0.074	<0.50	0.080	8.5
Reference Stations															
Hood Canal (Misery Point)	9-16-75	Staghorn Sculpin *Leptocottus armatus*	18	0.030	0.20	0.10	0.50	0.48	8.7	<1.0	0.30	0.021	1.9	---	9.0
Clam Bay	9-28-75	Rock Sole *L. bilineata*	28	0.050	14	<0.10	0.50	0.77	8.7	1.0	0.20	0.030	1.4	0.18	6.8

---

[a] NTS Navy Torpedo Station

been related to the relative proximity of the Clam Bay station to the Tacoma smelter (ASARCO) or other local sources of arsenic, the concentrations of arsenic measured in fishes from the Liberty Bay and Clam Bay stations appeared to be disproportionately low and, therefore, should be viewed with caution until they are confirmed.

Just as in the case of the shellfish, the levels of mercury measured in the muscle tissues of the fishes collected from Liberty Bay and the survey reference stations (0.030 - 0.15 ug/g) were below the proposed FDA action level for mercury in fish and shellfish of 0.5 ug/g (wet weight) (U.S. FDA, 1974).

Biological Characterization

Phytoplankton Production -

As mentioned earlier in the report, dense phytoplankton populations, of "bloom" proportions, were observed in Liberty Bay during the survey September 15, 1976. Based on total organic carbon (TOC) measurements (Table 2) and the tea-colored character of the populations, the bloom appeared to be located in the surface waters near Station WS-7 (Mid-Bay) during low tide. Under high tide conditions, the bloom was observed in surface waters near the Poulsbo STP outfall (Station WSF-3) and at the Sea Farms hatchery site (Station WSF-5).

The major phytoplankton and protozoan species present in the bloom as well as in other selected Liberty Bay surface waters during and following the survey are presented below.

Date	Station	Preservative	Species
9-15-76	WSF-5	Formalin	(Dinoflagellates)
	(Phytoplankton bloom observed)		*Prorocentrum gracile* *Gymnodinium splendens* *Glenodinium* sp. *Ceratium fusus* *Gyrodinium spirale*
			(Diatoms)
			Coscinodiscus wailsii
			(Ciliate Protozoans)
			Parundella lagena
9-15-76	W-11	Formalin	(Dinoflagellates)
	(No phytoplankton bloom observed)		*Prorocentrum gracile*
			(Diatoms)
			Thalassiosira sp.
			(Ciliate Protozoans)
			Parundella lagena
10-7-76	WS-7	Lugol's Solution	(Dinoflagellates)
	(No phytoplankton bloom observed)		*Prorocentrum gracile* *Gymnodinium variable* (minima) *Ceratium fusus* *Glenodinium* sp. *Gyrosigma fasciola* *Peridinium minutum*
			(Diatoms)
			Nitzschia closterium *Nitzschia seriata* *Skeletonema costatum* *Coscinodiscus wailsii* *Thalassiosira* sp.

Date	Station	Preservative	Species
			(Blue-Green Algae) *Spirulina* sp. ? (Ciliated Protozoans) *Parundella lagena* *Stenosomella pacifica*
10-7-75	North of Poulsbo Marina	Lugol's Solution	(Dinoflagellates) *Prorocentrum gracile* *Gymnodinium variable* (minima) *Glenodinium* sp. *Gyrosigma fasciola* *Peridinium ovatum* (Diatoms) *Nitzschia closterium* *Nitzschia seriata* *Nitzschia* sp. *Skeletonema costatum* *Coscinodiscus wailsii* *Thalassiosira rotula* *Chaetoceros vanheurkii* (Blue-Green Algae) *Spirulina* sp. ? (Ciliate Protozoans) *Stenosomella pacifica*

The algal bloom was composed primarily of the dinoflagellates *Prorocentrum gracile* and *Gymnodinium splendens*. The concentrations of these organisms present in surface waters at Station WS-7 during low tide (September 15, 1975) were 2.7 X 10^6 and 3.7 X 10^4 cells/ml, respectively. Several of the species identified in Liberty Bay waters following the survey (October 7, 1975) may also have been present during the bloom September 15, 1975. Formalin preservation of the survey samples may, however, have resulted in the destruction or deformation of the more fragile forms.

The organism tentatively identified as the blue-green alga, Spirulina sp., was thought to possibly be a bacterium. This organism, together with P. gracile and G. spendens, were the predominate species present at Station WS-7 and north of the Poulsbo marina on October 7, 1975. There was also some doubt about the identity of the dinoflagellate, Gymnodinium variable (minima). It was recognized that these organisms may have represented more than one species or perhaps the spores of symbiotic Gymnodiniods (Personal Communication, Dr. Richard Steele, EPA, Narragansett, RI).

When discussing algal blooms, questions are usually raised as to the cause of the blooms. Based on the work of Lincoln and Collias (1975), substantial blooms of phytoplankton can be supported in Liberty Bay as a result of nutrients entering the Bay from Port Orchard. As stated earlier, these investigators believed that nitrate and silicate were the nutrients limiting algal growth in the Port Orchard system. Lincoln and Collias (1975) also identified biological decomposition and slow flushing as the processes responsible for the relatively high ammonia levels measured in the deeper portions of the Bay. The origin of the decomposing organic material and the possible stimulatory effect of the elevated ammonia levels on algal growth were not made clear. They implied that the decomposition of the algal biomass produced during the spring phytoplankton bloom was primarily responsible for the generally higher ammonia concentrations. Considering the apparent nitrate limited character of Liberty Bay waters, ammonia and organic matter being discharged to the Bay by local STPs (Poulsbo's primary treatment plant in particular) should also be considered as potentially important nitrogen sources capable of supporting localized algal blooms.

Oyster Embryo Response -

Water

The response of Pacific oyster embryos to seawater collected from the Liberty Bay system, Clam Bay, and Hood Canal is presented in Tables 13 and 14. These data are plotted in Figures 29-32 to show the vertical and horizontal differences in embryo response measured September 15, 1975 under conditions of low and high tide. Although oyster embryo development and survival are the response parameters discussed below, shell growth was also observed to be a sensitive measure of water quality. In fact, pronounced differences in the size of normally developed larvae revealed subtle adverse effects not reflected by larval development or survival.

(Survival) Low Tide - Relative good larval survival (89.7 - 104%) was observed in waters collected from all depths at the Sea Farms site (Station WSF-5) and lower Bay (Stations W-11 and WSF-13) during low tide. Survival in these waters was similar to that observed in the Clam Bay and Hood Canal samples (92.9 - 105%). Larval survival in surface waters from Station WSF-3 near the Poulsbo STP outfall was only 71.5%. However, no larvae survived exposure to the surface waters from Station WS-7 in central Liberty Bay to which the algal bloom seemed to

Table 13. Pacific Oyster Embryo Survival (48-Hour) in Liberty Bay, Clam Bay, and Hood Canal Waters.

		Mean Per Cent Relative Survival[a]						
		Liberty Bay Stations					Reference Stations[b]	
Tidal Stage	Sampling Depth	WSF-3	WSF-5	WS-7	W-11	WSF-13	Hood Canal	Clam Bay
Low	Surface	71.5	104	0	85.2	100	105	105
	Mid-Depth	88.3	89.8	61.6	98.4	101	92.9	101
	Bottom	90.7	94.8	94.5	96.7	89.7	101	94.1
	(Station Mean)	(83.5)	(96.2)	(52.0)	(93.4)	(96.9)	(99.6)	(100)
High	Surface	41.6	20.2	77.5	79.6	96.3	105	105
	Mid-Depth	99.9	97.9	92.4	83.5	83.7	92.9	101
	Bottom	100	89.8	81.1	91.5	99.4	101	94.1
	(Station Mean)	(80.5)	(69.3)	(83.7)	(84.9)	(93.1)	(99.6)	(100)

---

a Relative to survival in Clam Bay (bioassay control) seawater.

b Carry along control: 94.5% survival.

Table 14. Pacific Oyster Embryo Development (48-Hour) in Liberty Bay, Clam Bay, and Hood Canal Waters.

		Mean Percent Abnormal Larvae						
		Liberty Bay Stations					Reference Stations	
Tidal Stage	Sampling Depth	WSF-3	WSF-5	WS-7	W-11	WSF-13	Hood Canal	Clam Bay
	Surface	3.1	1.7	-	0.4	0.5	0.8	0.7
Low	Mid-Depth	0.4	1.3	1.1	1.1	0.7	1.1	0.5
	Bottom	0.8	0.4	0.4	1.4	0.6	1.2	0.4
	(Station Mean)	(1.4)	(1.1)	-	(0.97)	(0.60)	(1.0)	(0.5)
	Surface	6.4	95.8	0.7	25.3	4.4	0.8	0.7
High	Mid-Depth	0.8	0.7	1.1	0.8	2.9	1.1	0.5
	Bottom	0.3	0.0	0.2	1.3	0.7	1.2	0.4
	(Station Mean)	(2.5)	(32.2)	(0.67)	(9.1)	(2.7)	(1.0)	(0.5)

a Clam Bay (bioassay control): 0.4% abnormality

b Carry along control: 0.5% abnormality

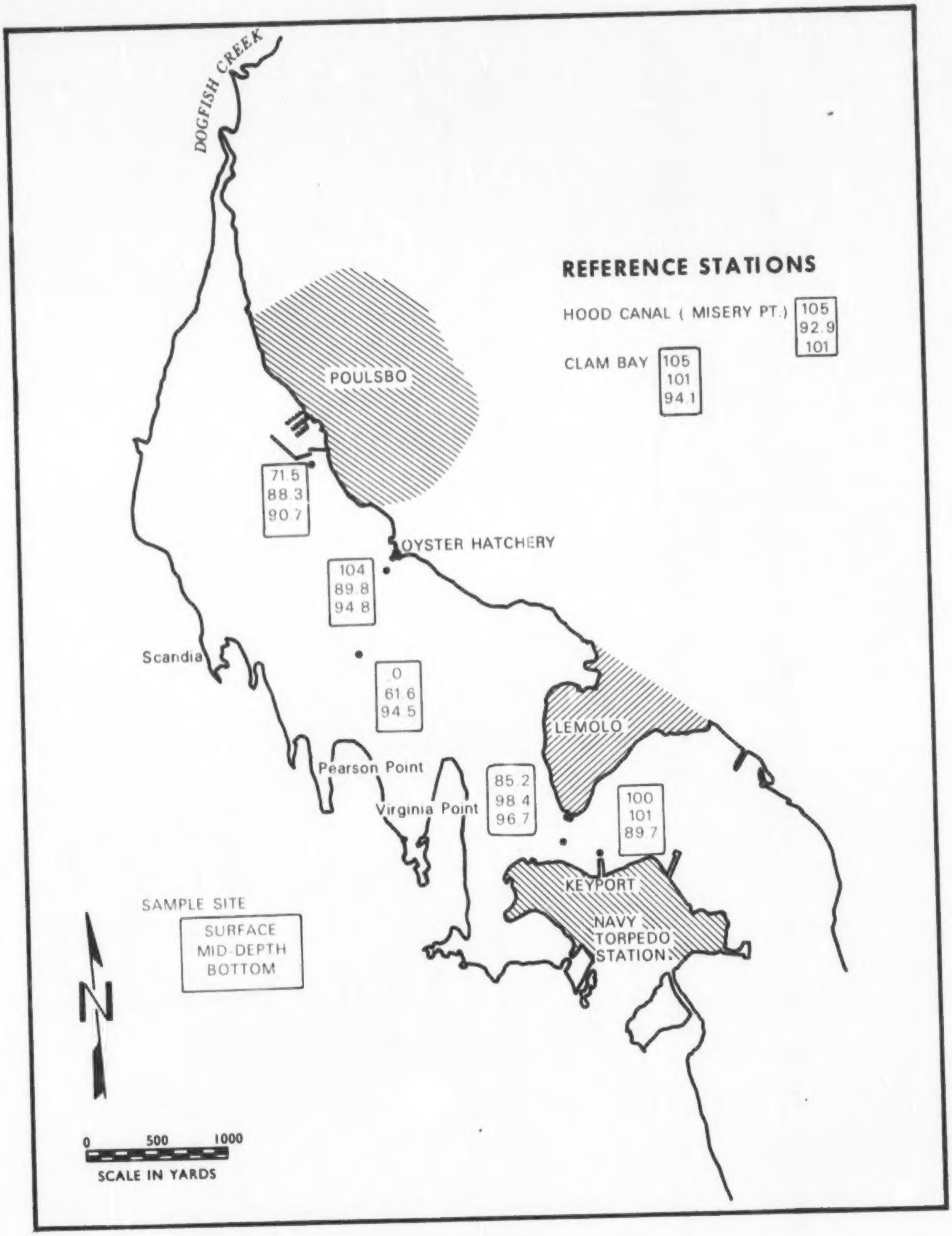

DOGFISH CREEK
REFERENCE STATIONS
HOOD CANAL (MISERY PT.)
105
92.9
101
CLAM BAY
105
101
94.1
POULSBO
71.5
88.3
90.7
OYSTER HATCHERY
104
89.8
94.8
Scandia
0
61.6
94.5
LEMOLO
Pearson Point
Virginia Point
85.2
98.4
96.7
100
101
89.7
KEYPORT
NAVY TORPEDO STATION
SAMPLE SITE
SURFACE
MID-DEPTH
BOTTOM
N
0
500
1000
SCALE IN YARDS

Figure 29. Relative per cent survival of Pacific oyster embryos in Liberty Bay waters collected during low tide.

be primarily confined. A well defined vertical response gradient was also observed at this station, with 61.6% and 94.5% survival occurring in middepth and bottom waters, respectively.

High Tide - Under high tide conditions, a slight general decline in survival was observed in waters from Stations W-11 and WSF-13, with survival values ranging from 79.6% to 96.3%. Although larval survival in surface waters from Station WSF-3 dropped from 71.5% to 41.6%, the most pronounced changes in survival associated with increased tide height were observed in waters from Stations WSF-5 and WS-7. The percentage of larvae surviving in surface waters from Station WS-7 jumped from 0% to 77.5%, while larval survival in surface waters from Station WSF-5 declined from 104% to 20.2%, reflecting a substantial reduction in water quality in the vicinity of the Sea Farms seawater intake.

These changes in larval response appeared to be directly related to the tidal movement of the algal bloom away from Station WS-7 toward the Sea Farms hatchery site (Station WSF-5). This shift in the location of the bloom was observed visually as well as being reflected by pronounced increases in surface water total organic carbon (TOC) levels at Stations WSF-3 and WSF-5 (Table 15). The possible adverse influence of algal bloom conditions on larval survival was also supported by correlation analysis showing a high negative correlation between TOC levels and larval survival during both high and low tide ($r = -0.87$).

(Development) Low Tide - Determinate larval abnormalities in Liberty Bay waters collected during low tide ranged from 0.4% at several stations to a high of 3.1% in surface waters from Station WSF-3 near the

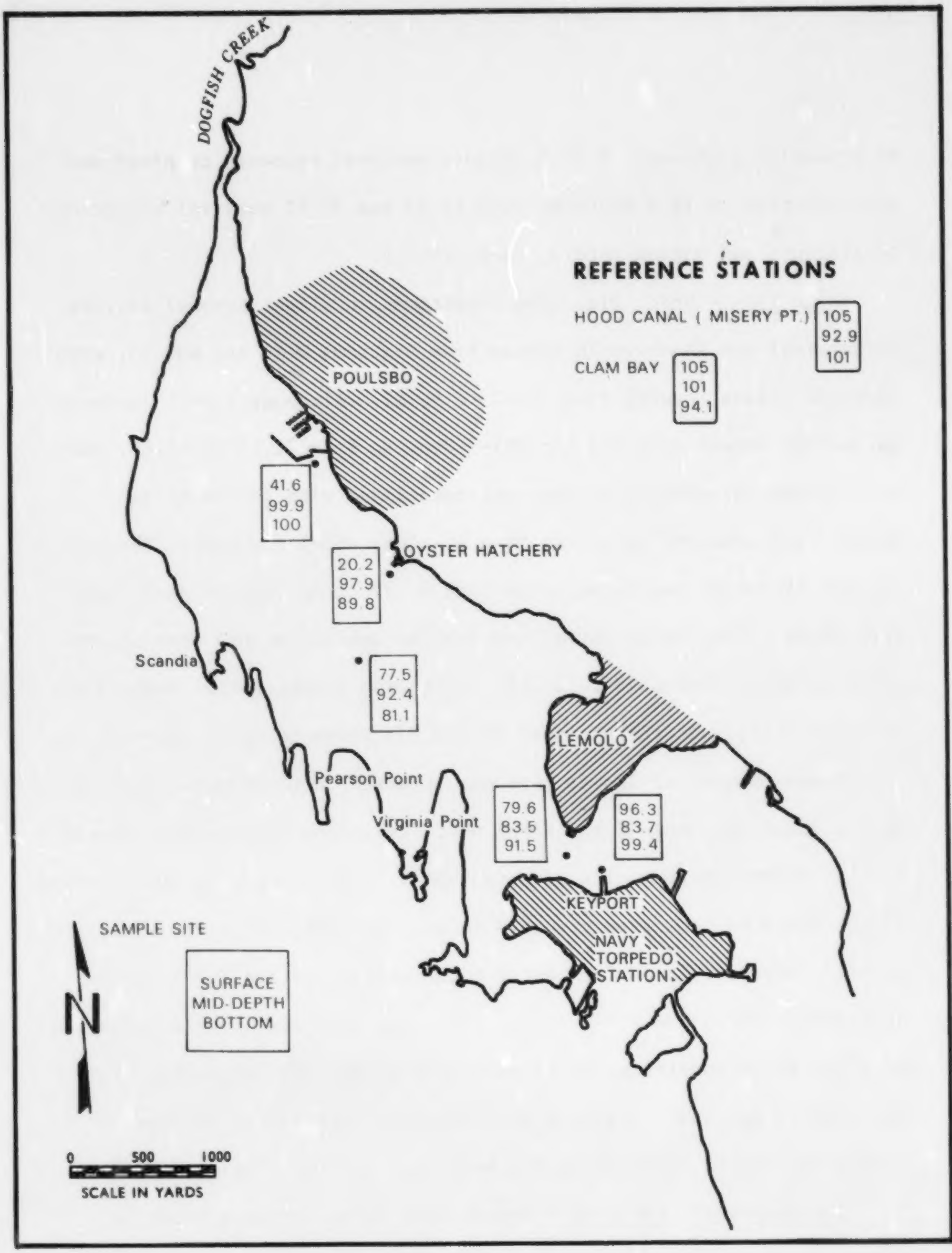

DOGFISH CREEK
REFERENCE STATIONS
HOOD CANAL (MISERY PT.)
105
92.9
101
CLAM BAY
105
101
94.1
POULSBO
41.6
99.9
100
OYSTER HATCHERY
20.2
97.9
89.8
Scandia
77.5
92.4
81.1
LEMOLO
Pearson Point
Virginia Point
79.6
83.5
91.5
96.3
83.7
99.4
KEYPORT
NAVY
TORPEDO
STATION
SAMPLE SITE
SURFACE
MID-DEPTH
BOTTOM
N
0
500
1000
SCALE IN YARDS

Figure 30. Relative per cent survival of Pacific oyster embryos in Liberty Bay waters collected during high tide.

Table 15. Pacific Oyster Embryo Responses as Related to Total Organic Carbon Levels in Liberty Bay Waters.

Stations	Tidal Stage	Depth (m)	Total Organic Carbon (mg/l)	Mean Per Cent Abnormal Larvae	Mean Per Cent Relative Larval Survival
Liberty Bay Stations					
WSF-3 (Near Poulsbo STP Outfall)	Low	0	9.0	3.1	71.5
		3	2.0	0.4	88.3
		6	3.0	0.8	90.7
	High	0	16.0	6.4	41.6
		5	3.0	0.8	99.9
		9	3.0	0.3	100
WSF-5 (Oyster Hatchery Site)	Low	0	4.0	1.7	104
		3	3.0	1.3	89.8
		6	3.0	0.4	94.8
	High	0	17.0	95.8	20.2
		5	2.0	0.7	97.9
		9	2.0	0.0	89.8
WS-7 (Mid-Bay)	Low	0	50.0	-	0.0
		3	3.0	1.1	61.6
		6	3.0	0.4	94.5
	High	0	-	0.7	77.5
		5	-	1.1	92.4
		9	-	0.2	81.1
W-11 (South Bay)	Low	0	2.0	0.4	85.2
		5	3.0	1.1	98.4
		9	3.0	1.4	96.7
	High	0	4.0	25.3	79.6
		6	2.0	0.8	83.5
		12	2.0	1.3	91.5
WSF-13 (Keyport STP Outfall)	Low	0	3.0	0.5	100
		6	3.0	0.7	101
		12	3.0	0.6	89.7
	High	0	-	4.4	96.3
		7	-	2.9	83.7
		14	-	0.7	99.4
Reference Stations					
Hood Canal (Misery Point)	Low	0	-	0.8	105
		3	-	1.1	92.9
		6	-	1.2	101
Clam Bay	Low	0	-	0.7	105
		5	-	0.5	101
		10	-	0.4	94.1

---

a Relative to survival in Clam Bay (bioassay control) seawater

b Carry along control: 0.5% abnormality; 94.5% survival

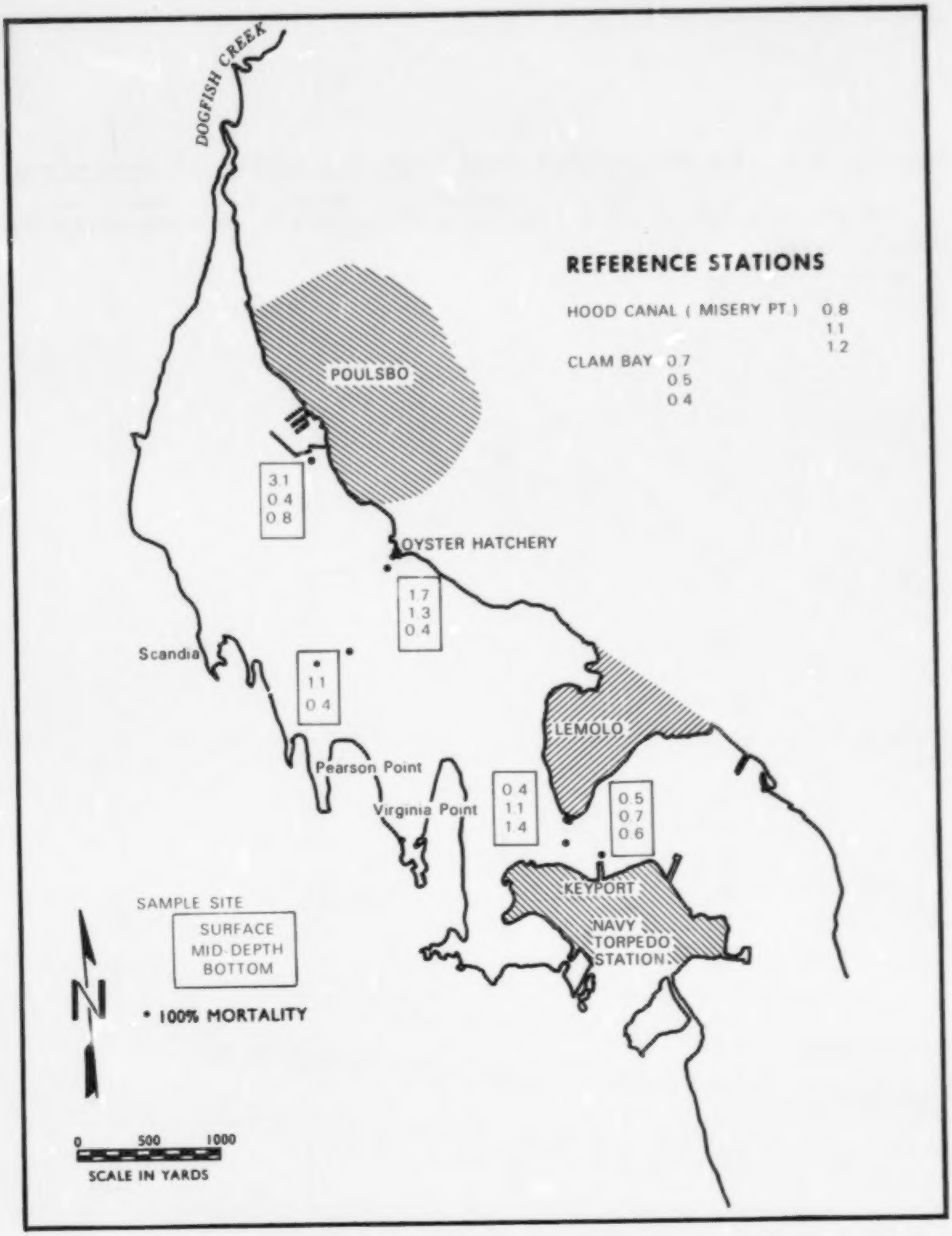

DOGFISH CREEK
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) 0.8
1.1
1.2
CLAM BAY 0.7
0.5
0.4
POULSBO
3.1
0.4
0.8
OYSTER HATCHERY
1.7
1.3
0.4
Scandia
1.1
0.4
LEMOLO
Pearson Point
Virginia Point
0.4
1.1
1.4
0.5
0.7
0.6
KEYPORT
NAVY TORPEDO STATION
SAMPLE SITE
SURFACE
MID-DEPTH
BOTTOM
N
• 100% MORTALITY
0
500
1000
SCALE IN YARDS

Figure 31. Per cent abnormal development of Pacific oyster embryos in Liberty Bay waters collected during low tide.

Poulsbo STP outfall. No mean percent abnormal larvae could be calculated for Station WS-7 surface waters, however, because of the complete mortality that occurred in these samples. Although this mortality certainly raised questions about the quality of water in the central Bay (Station WS-7), all the determinate abnormality values were well below Woelke's (1972) proposed single sample receiving water quality criterion of 20% abnormality, as well as his multiple sample criterion of 5% abnormality.

High Tide - The changes in larval abnormality observed between low and high tide generally paralleled the tide-related changes in larval survival described earlier. Larval abnormalities in waters collected from the lower Bay during high tide increased substantially, particularly in the surface waters from Station W-11, in which 25.3% abnormality was observed. Larval abnormality observed in surface waters from Station WSF-3 increased slightly from 3.1% to 6.4%, while abnormality in surface waters from Station WSF-5 rose from 1.7% to 95.8%. These changes were associated with a marked improvement in surface water quality at Station W-7.

Just as in the case of larval survival, the presence or absence of algal bloom conditions appeared to have a distinct influence on the outcome of larval development. Although the cause of the increase in larval abnormality at Station W-11 was not entirely understood, TOC levels were positively correlated with larval abnormality during both tidal stages studied (r = 0.70).

Sediment

The bioassay of Liberty Bay sediments using Clam Bay seawater as

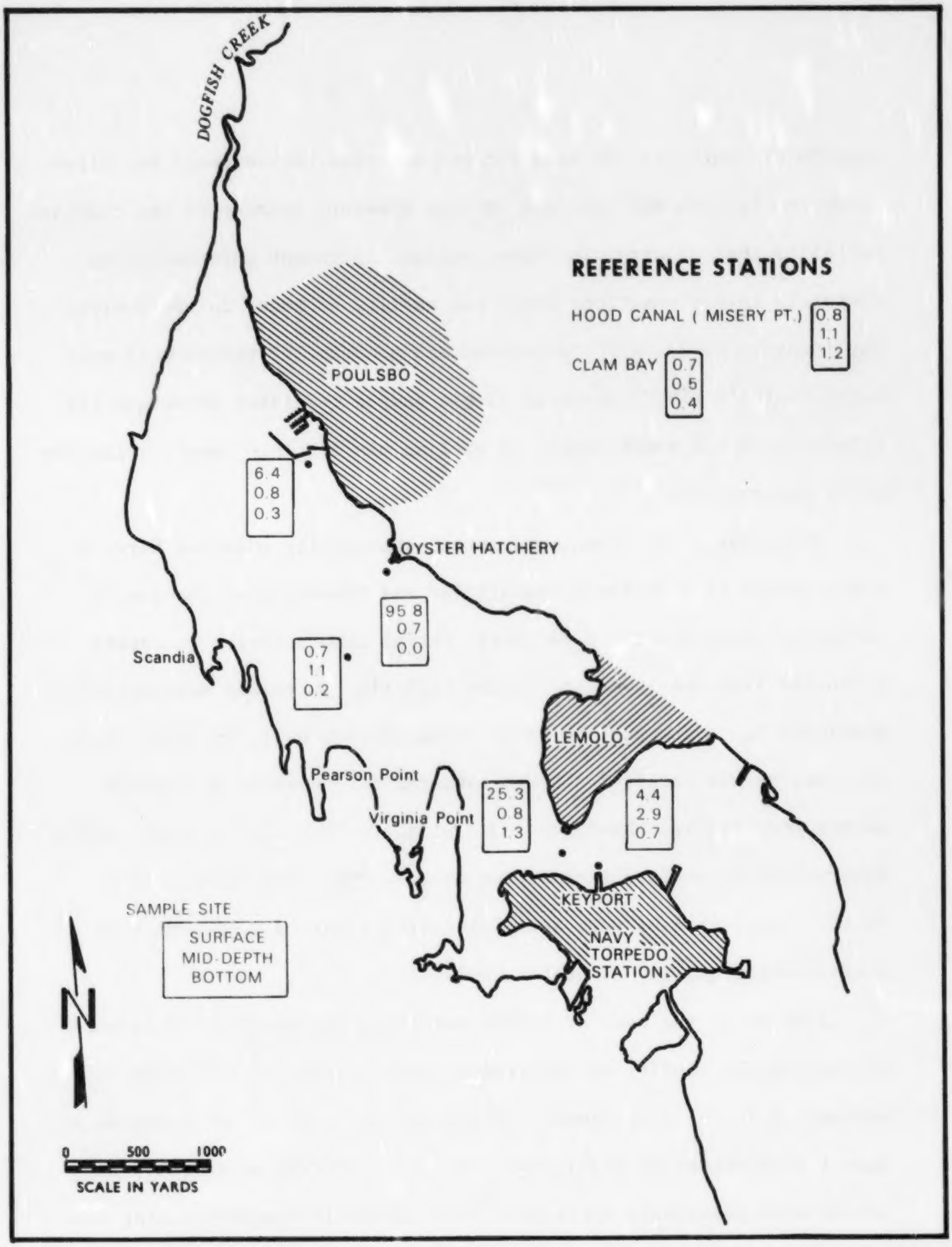

DOGFISH CREEK
REFERENCE STATIONS
HOOD CANAL (MISERY PT.) 0.8 1.1 1.2
CLAM BAY 0.7 0.5 0.4
POULSBO
6.4 0.8 0.3
OYSTER HATCHERY
95.8 0.7 0.0
Scandia
0.7 1.1 0.2
LEMOLO
Pearson Point
Virginia Point
25.3 0.8 1.3
4.4 2.9 0.7
KEYPORT
NAVY TORPEDO STATION
SAMPLE SITE
SURFACE
MID-DEPTH
BOTTOM
N
0
500
1000
SCALE IN YARDS

Figure 32. Per cent abnormal development of Pacific oyster embryos in Liberty Bay waters collected during high tide.

the diluent provided information on the relative toxicities of the various sediments tested. The effects observed, however, did not necessarily reflect the effects that would have occurred had the sediments been diluted with Liberty Bay seawater.

Pacific oyster embryo response to surface sediments from Liberty Bay, Clam Bay, and Hood Canal is shown in Table 16. The effect of Liberty Bay sediments on larval survival was considered to be minor considering the 85 - 99% survival observed at sediment concentrations of 10 g/l. These sediments were also found to have only a limited effect on oyster embryo development. Most larval abnormalities occurring in the 10 g/l sediment concentrations ranged from 1.1 - 2.5%, while 15.3% abnormality was associated with surface sediments from central Liberty Bay (Station WS-7). This high value exceeded the upper range of abnormalities associated with (10 g/l) surface sediments from Clam Bay and Hood Canal. Based on data collected by Schink, Westley, and Woelke (1974) using a modified oyster embryo assay technique, sediment core composites from Grays Harbor, Bellingham Bay, Henderson Inlet, Pt. Whitney Lagoon, and the Duwamish River appeared to be considerably more toxic to oyster embryos, however, than were the surface sediments from Station WS-7.

Correlation analysis performed by Schink and his associates (1974) indicated that the total sulfides concentration was the variable most strongly correlated with the response of larvae to the core composites they assayed. Total sulfides, zinc, sediment particle size, BOD, and total phosphorus were also found, by step-wise multiple regression analysis, to have accounted for 93% of the observed variation in larval response.

Table 16. Pacific Oyster Embryo Responses (48-Hour) to Seawater Suspensions of Liberty Bay Surface Sediments.

Station	Sediment Concentrations[a] g/1 (Wet Weight)	(Dry Weight)	Mean % Abnormal Larvae	Mean % Relative Larval Survival[b]
Liberty Bay Stations				
WSF-3 (Near Poulsbo STP Outfall)	10	4.4	2.5	98.0
	1.0	0.44	0.5	101
	0.10	0.044	1.0	102
	0.01	0.0044	1.0	99.6
WSF-5 (Oyster Hatchery Site)	10	3.4	1.1	91.9
	1.0	0.34	0.6	97.0
	0.10	0.034	0.4	96.9
	0.01	0.0034	0.5	97.2
WS-7 (Central Bay)	10	4.4	15.3	88.8
	1.0	0.44	0.7	96.5
	0.10	0.044	0.6	111
	0.01	0.0044	0.7	103
WSF-13 (Keyport STP Outfall)	10	6.9	1.4	85.0
	1.0	0.69	0.3	109
	0.10	0.069	1.4	100
	0.01	0.0069	0.4	96.5
Reference Stations				
Hood Canal (Misery Point)	10	7.8	0.3	106
	1.0	0.78	0.4	99.6
	0.10	0.078	0.8	84.9
	0.01	0.0078	0.6	94.6
Clam Bay	10	6.5	1.0	101
	1.0	0.65	0.5	101
	0.10	0.065	0.2	90.2
	0.01	0.0065	0.7	99.1

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[a] Clam Bay (Bioassay Control) seawater used as diluent.

[b] Relative to survival in seawater diluent.

The dry weight equivalent concentrations of total sulfides, metals, and total volatile solids present in each 10 g/1 (wet weight) Liberty Bay sediment concentration assayed are presented in Table 17. Sediment concentrations as high as 10 g/1 (wet weight) would usually only be associated with dredging or spoil disposal operations. This concentration was selected for inclusion in Table 17, however, because it was the only concentration that, in some cases, appeared to adversely affect larval response. Comparison of the various parameters listed failed to reveal the positive correlation between total sulfides and oyster embryo response reported by others. Although higher concentrations of total volatile solids were definitely associated with increased larval abnormalities, a better understanding of the individual and combined effects of sulfides, volatile solids, metals, and other sediment parameters on embryo development and survival can only be obtained by further study.

Sewage Treatment Plant Effluents

The acute toxicities of treated effluent composites collected 9-15 and 16-76 from the Poulsbo, Keyport, and Torpedo Station STPs are listed in Table 18. As in the case of the sediment bioassays, the toxicities of the effluents diluted with Clam Bay seawater were believed to approximate, but not necessarily duplicate, effluent toxicities in Liberty Bay seawater.

The relative toxicities of the various STP effluents tested followed the order: Poulsbo > Torpedo Station > Keyport. Waste discharge from the Poulsbo plant was most toxic from the standpoint of both larval

TABLE 17. Pacific Oyster Embryo Responses (48-Hour) Associated with Actual Concentrations of Metals, Total Sulfides, and Total Volatile Solids Contributed by 10 g/1 (Wet Weight) Sediment Treatments.

	Concentration (ug/1)													Oyster Embryo Response	
Station	Antimony (Sb)	Arsenic (As)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Manganese (Mn)	Mercury (Hg)	Nickel (Ni)	Zinc (Zn)	Total Sulfides	Total Volatile Solids (g/1)	Mean % Abnormal Larvae	Mean % - Relative Larval Survival
Liberty Bay Stations															
WSF-3 (Near Poulsbo STP Outfall)	0.88	35	12	150	130	79,000	79	750	0.48	220	290	1600	0.21 g	2.5	98.0
WSF-5 (Oyster Hatchery Site)	<0.34	37	44	180	220	110,000	320	1100	0.61	370	820	4400	0.24 g	1.1	91.9
WS-7 (Central Bay)	<0.44	57	16	200	200	120,000	200	1100	0.70	280	530	1400	0.34 g	15.3	88.8
WSF-13 (Keyport STP Outfall)	<0.69	35	12	150	90	83,000	160	760	0.53	160	360	2300	0.21 g	1.4	85.0
Reference Stations															
Hood Canal (Misery Point)	<0.78	55	9.4	220	160	140,000	47	3800	0.20	400	420	299	0.09 g	0.3	106
Clam Bay	23	39	6.5	140	140	78,000	200	680	0.63	120	650	600	0.11 g	1.0	101

TABLE 18. Pacific Oyster Embryo Responses (48 Hour) to Treated Effluents from Three Sewage Treatment Plants Discharging into Liberty Bay or Nearby Waters.

Source of Treated Effluent[a]	Approximate EC50[b] (ml/l)	Approximate LC50[c] (ml/l)
Poulsbo STP	20	25-50
Navy Torpedo Station STP	45	> 200
Keyport STP	140	> 200

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[a] Clam Bay (Bioassay Control) seawater used as diluent

[b] Concentration of effluent resulting in 50% larval abnormality

[c] Concentration of effluent resulting in 50% larval mortality

abnormality and lethality. The approximate 48-hour EC50[a] and LC50[b] of this waste were 20 ml/1 and 25-50 ml/1, respectively. Treated effluent from the Torpedo Station STP was characterized by an EC50 of 45 ml/1, while the EC50 of the Keyport STP effluent was 140 ml/1. Both the Torpedo Station and Keyport STP discharges were characterized by an indeterminately high LC50 of >200 ml/1.

Comparison of the effluent EC50 and LC50 values with respect to flow are presented in Table 19 for the purpose of showing the potential acute toxic impacts of the STP effluents on the Liberty Bay system. The Poulsbo STP had the greatest potential toxic impact, discharging 53.0×10^6 EC50 units or 21.2×10^6 - 42.4×10^6 LC50 units per day. Least potentially toxic was the Keyport STP effluent. The daily discharge from this facility was $<0.541 \times 10^6$ EC50 units or $<0.379 \times 10^6$ LC50 units. The Torpedo Station effluent was intermediate in potential toxicity, discharging 9.24×10^6 EC50 units or $<2.08 \times 10^6$ LC50 units per day to the Liberty Bay system.

Biological Significance of Various Chemical and Biological Factors -

The cause(s) of the recurrent mortalities of Pacific oyster embryos and larvae reported by Sea Farms, Inc. was not definitely determined. Several factors were identified, however, that alone or in combination with each other, may have contributed to the Sea Farms problem. These factors included algal blooms, sewage treatment plant effluents, sulfides,

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[a] EC50 - Concentration of effluent resulting in 50% larval abnormality

[b] LC50 - Concentration of effluent resulting in 50% larval mortality

TABLE 19. Estimated Number of Acute Toxic Units Discharged Daily to the Liberty Bay System by Local Sewage Treatment Plants.

Parameter	Sewage Treatment Plant Poulsbo	 Torpedo Station	 Keyport
Flow:			
(MGD)	0.28	0.11	0.02[a]
(ml /day)	10.6×10^8	4.16×10^8	0.757×10^8
Approximate EC50[b] (ml/l)	20	45	140
EC50 Units Discharged Per Day	53.0×10^6	9.24×10^6	0.541×10^6
Approximate LC50[b] (ml/l)	25-50	>200	>200
LC50 Units Discharged Per Day	$21.2 \times 10^6 - 42.4 \times 10^6$	$<2.08 \times 10^6$	$<0.379 \times 10^6$

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[a] Estimated

[b] Based on 48-Hour Oyster Embryo Assay

EC50 Concentration of effluent resulting in 50% larval abnormality

LC50 Concentration of effluent resulting in 50% larval mortality total volatile solids, untreated plating wastes, metal laden sediments, and PBI-sensitive substances. The possible biological significance of some of these factors has already been presented; others are discussed in more detail below.

Mercury

No major sources of mercury or evidence of serious mercury contamination were found during the survey. Consequently, excessive mercury concentrations in Liberty Bay waters did not appear to be a probable cause of the mortality problems experienced by Sea Farms, Inc. The report of mercury levels in Liberty Bay as high as 110 ug/l could not be substantiated. Any evidence confirming this report would have been very significant. The acute toxicity of mercury (as HgCl) to Pacific oyster embryos was reported to be 32 ug/l (Okubo and Okubo, 1962). More recently, Calabrese and Nelson (1974) observed a 50% mortality of embryos of American oysters, C. virginica, and hard clams, Mercenaria mercenaria, in 48 hours at mercury concentrations of only 5.6 ug/l and 4.8 ug/l, respectively.

When relating these acute toxicity data, as well as the other 48-hour bioassay results presented in this report, to the Sea Farms problem it should be understood that most of the mortalities reported by Sea Farms occurred a week or more following spawning. This does not necessarily mean that exposure periods of a week or more were involved. However, had the experimental bioassay protocols included similar exposure periods, the toxicities of the various agents tested would have appeared even greater since less material would most likely have been required to produce the effects originally observed at the end of 48 hours.

Other Metals

Because of the analytical problems encountered during the seawater metals analyses, it was not possible to assess the biological significance of other metals levels in Liberty Bay seawater. It was possible, however, to estimate the seawater metals concentrations that could have occurred in Liberty Bay following continuous and intermittent bypasses of metallic plating wastes from the Torpedo Station (Table 20). These estimates were made using the following formulas:

(Continuous Discharge)

Under the conditions described below, the steady state concentration, C_s, in Liberty Bay is given by:

$$C_s = \frac{Q_w}{Q_{tide}} \times C_w$$

where:

Q_w = waste flow c.f.s.

C_w = waste concentration, mg/1

Q_{tide} = tidal exchange rate, c.f.s.

$$C_s = \frac{Q_w}{50{,}000}$$

Assumptions,

1. Entire portion of Liberty Bay is completely well mixed during one tidal cycle.
2. Water coming in on a flood tide carries no residual from the previous ebb.
3. Only inflow to Liberty Bay is from waste discharge.
4. Waste flow rate is 3141 GPH.

Table 29. Estimated Total Metal Concentrations in Liberty Bay Seawater Resulting from Bypassing Plating Wastes at the Navy Torpedo Station, Keyport, Washington.

Element	Possible Background Total Metal Concentrations in Seawater[a] (ug/1)	Suggested Hazardous Total Metal Concentration in Seawater[b] (ug/1)	Concentration ug/1 Intermittent Bypass[c] 2-Hour Duration Flow Rate (GPH) (3141)			Continuous Bypass[d] Flow Rate (GPH) (3141)		
				(2082)	(197)		(2082)	(167)
Cadmium (Cd)	0.08	≥10	0.26	0.20	0.09	0.22	0.17	0.09
Chromium (Cr)	0.3	>10	1.1	0.80	0.34	0.87	0.68	0.33
Copper (Cu)	1.1	≥50	1.1	1.1	1.1	1.1	1.1	1.1
Lead (Pb)	1.2	≥50	1.2	1.2	1.2	1.2	1.2	1.2
Mercury (Hg)	0.1[b]	≥0.10	0.1	0.1	0.1	0.1	0.1	0.1
Nickel (Ni)	4.3	≥100	7.8	6.6	4.5	7.0	6.1	4.4
Zinc (Zn)	6.2	≥100	6.2	6.2	6.2	6.2	6.2	6.2

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[a] Source: Davey and Soper, 1975 (Narragansett Bay)

[b] Source: National Academy of Sciences, Water Quality Criteria, 1972

[c] Concentrations in upper 3-meter water column at Sea Farms Hatchery site

[d] Concentrations throughout Liberty Bay

5. Tidal amplitude is 6 feet.

6. Surface area of Liberty Bay is 0.45×10^8 square feet.

7. Tidal period is 12.4 hours.

(Intermittent Discharge)

Under the conditions described below, the concentration, C, for an intermittent discharge during the time t=o to t=t, at some point, x, downstream from the discharge is:

$$C = \frac{Q_w * 10^6}{A\rho(4\pi\kappa)^{\frac{1}{2}}} \int_{t_0}^{t_1} \frac{1}{\sqrt{t_1-\tau}} \, e^{\frac{-(x-u(t_1-\tau))^2}{4\kappa(t_1-\tau)}} \, d\tau$$

where:

Q_w = mass loading rate, lbs/sec

A = cross-sectioned area at point of discharge, square feet

ρ = density of discharge, lbs/ft^3

κ = diffusion coefficient, ft^2/sec

u = velocity of receiving water, feet/sec

τ = during time variable, seconds

x = longitudinal distance downstream, feet

Assumptions,

1. Well mixed vertically over a depth of 3.0 meters.

2. Lateral boundaries do not influence diffusion or dispersion processes.

Calculations were made using the highest metal concentrations measured in the plating plant sump or plating treatment plant effluent during the Compliance Monitoring Inspection (EPA, 1975). The flow rates on which the estimates were based represented the highest, median, and lowest flows of bypassed plating waste actually measured by the Navy during 16 bypasses reported from March 10, 1975 to September 17, 1975. For purposes of comparison, Table 20 also includes the hazardous metal concentrations suggested by the National Academy of Sciences (1972) for oyster growing waters. Most of the background total metals levels used in the calculations were based on the analysis of Narragansett Bay seawater (Davey and Soper, 1975). These levels were generally similar, however, to unpublished total metal concentrations recently measured in Puget Sound by other investigators (Personal Communication, Dick Huntamer, Seattle, WA).

Under the worst possible conditions, characterized by the stratified dilution of an intermittent 3141 GPH bypass, none of the estimated individual metal concentrations exceeded suggested hazardous levels at the Sea Farms hatchery site. The combined effect of these estimated metal concentrations was evaluated by determining whether or not they exceeded a hazardous level defined by the formula presented below (National Academy of Sciences, 1972).

$$\frac{C_a}{L_a} + \frac{C_b}{L_b} + \ldots + \frac{C_n}{L_n} \leq 1.0 \text{ (Hazardous Concentration)}$$

where:

C = Estimated concentrations following intermittent 2-hour bypass (3141 GPH)

L = Suggested hazardous levels not to be exceeded

Although this application of the formula exceeded its intended use, the results suggested that the combined contributions of metals would also not have exceeded a hazardous level by the time they reached the Sea Farms site.

It is important to note that many of the hazardous levels suggested by the National Academy of Sciences were found to be in reasonable agreement with metal concentrations estimated to be safe for oyster embryos of the genus Crassostrea (Table 21). The estimated "safe" concentrations were generated by multiplying known 48-hour LC50 values by an appropriate application factor (ratio of safe to lethal concentrations) suggested by the Academy (1972).

Sewage Treatment Plant Effluents

The bioassay of the STP effluents provided information on the relative toxicities of the treated wastes as described earlier. By applying appropriate application factors (safety factors) to these data it was possible to also estimate the "safe" dilutions of the various wastes and compare these values with the minimum dilutions of the wastes estimated to occur at a point 1000 meters from their source (Table 22). This technique provided a means of assessing the potential impact of the STP effluents on the Sea Farms hatchery operation under a variety of realistic tidal speeds and diffusion rates.

Estimates of the minimum waste dilutions were computed by the use of the following formula (Pearson, 1961):

$$S_{min} = 3.64 \frac{D\ u\ y\ x}{Q}$$

where:

D = water depth, meters

Table 21. Estimated Safe Concentrations of Various Metals to Oyster Embryos of the Genus Crassostrea.

Element	Suggested Application Factor[a]	48-Hour EC50[b] or LC50[c] (ug/l)	Species	Reference	Estimated Safe Concentration (Factor X 48-Hr. EC50 or LC50)(ug/l)	Suggested Hazardous Concentration (ug/l)
Arsenic (As)	0.01	7500	Crassostrea virginica	Calabrese et. al.,1973)	75	≥50
Cadmium (Cd)	0.01	920[b] 3800	C. gigas C. virginica	(Cardwell et. al., In prep.) (Calabrese et. al., 1973)	9.2 38	≥10
Chromium (Cr)	0.01	10300	C. virginica	"	103	≥10
Copper (Cu)	0.01	103	C. virginica	"	1.0	≥50
Lead (Pb)	0.02	2450	C. virginica	"	24.5	≥50
Manganese (Mn)	0.02	16000	C. virginica	"	320	≥100
Mercury (Hg)	0.01[d]	5.6	C. virginica	"	0.06	≥0.1
Nickel (Ni)	0.02	1180	C. virginica	"	23.6	>100
Zinc (Zn)	0.01	310	C. virginica	"	3.1	≥100

[a] Source: National Academy of Sciences (1972)

[b] Concentration resulting in 50% larval abnormality

[c] Concentration resulting in 50% larval mortality

[d] Assigned

Table 22. Estimated Minimum Dilution of Sewage Treatment Plant Effluents 1000 Meters from Their Source Under Different Tidal Speeds and Diffusion Rates

Effluent Source (Distance from Sea Farms Hatchery Site, meters)	Approximate EC50 (Dilution[a])	Application Factor[c]	Estimated Safe Dilution[a]	Estimated Minimum Dilution[a]			
				Diffusion Coefficient[b] (m^2/second)			
				0.1		1.0	
				(Tidal Speed[b] (m/second))		(Tidal Speed[b] (m/second))	
				(5.79 X 10^{-2})	(2.04 X 10^{-1})	(5.79 X 10^{-2})	(2.04 X 10^{-1})
Poulsbo STP (870)	50	0.01 (1/100) 0.05 (1/20)	5,000 1,000	1,070	2,010	1,850	3,480
				(1.00 X 10^{-1})	(6.71 X 10^{-1})	(1.00 X 10^{-1})	(6.71 X 10^{-1})
Navy Torpedo Station STP (2510)	22	0.01 (1/100) 0.05 (1/20)	2,200 440	7,000	18,000	12,100	31,100
				(1.00 X 10^{-1})	(6.71 X 10^{-1})	(1.00 X 10^{-1})	(6.71 X 10^{-1})
Keyport STP (2560)	7	0.01 (1/100) 0.05 (1/20)	700 140	60,000	100,000	100,000	100,000

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[a] Dilutions presented as 1:X
[b] Source: Roats Engineering, 1970
[c] Source: National Academy of Sciences, Water Quality Criteria, 1972.

y = lateral coefficient of eddy diffusivity, meters^2/second

u = longitudinal speed of advections, meters/second

Q = waste discharge rate, meters^3/second

x = longitudinal distance downstream, meters

Assumptions,

1. Steady state horizontal diffusion and advection processes are the primary mechanisms dispersing the waste during a tidal cycle.
2. Wastes are mixed uniformly over a depth of 3 meters at the surface. The thickness of this layer does not change even though water depth increases.
3. Horizontal advection speeds can be obtained from float studies performed during 1964 and 1970 by Roats Engineering, Poulsbo, Washington (1970).

Based on these estimates, treated discharges from the Torpedo Station and Keyport STPs would have been sufficiently diluted at a point less than halfway to the hatchery site to be considered safe for exposure to Pacific oyster embryos regardless of the tidal speed, diffusion rate, or inherent safety of the application factor applied. Using the smallest application factor presented (0.05; 1/20), effluent from the Poulsbo STP would have been diluted enough 1000 meters from the outfall to be considered safe for exposure to oyster embryos. The fact that the outfall was only 870 meters up-Bay from the Sea Farms site raises some questions, however, about the adequacy of the dilution, particularly at lower tidal speeds.

Although the application of a safety factor of 0.05 (1/20) to STP effluents is not unreasonable, the National Academy of Sciences (1972) suggested applying factors of 0.01 (1/100) and 0.02 (1/50) to most of the potentially toxic constituents, primarily metals, found in the treated wastes being discharged to Liberty Bay. Assessments of the potential impact of these wastes should, therefore, at least be based on safety factors that are consistent with the most toxic constituents present. Consequently, the application of a safety factor of 0.01 (1/100) to the Poulsbo STP effluent indicated that under certain conditions these wastes would not have been significantly diluted by the time they reached the Sea Farms site to be considered "safe" for oyster embryos.

The fact that estimated dilutions of treated wastes from the Poulsbo STP did not, in every case, exceed the dilutions of this effluent estimated to be safe to oyster embryos certainly does not establish the Poulsbo STP as being the sole source of Sea Farms' problems. It does suggest, however, that these treated wastes may have contributed, at one time or another, to the reported mortalities of oyster embryos and larvae.

Phytoplankton, Bacteria, and Fungi -

Undefined conditions associated with the dense phytoplankton populations that were present in east-central Liberty Bay during the survey (September 15, 1976) appeared to have adversely affected the laboratory development and survival of Pacific oyster embryos more than any other factor. Although it was not determined what agent or which organism was responsible for the poor embryo response, the dinoflagellates, as well as associated bacteria and fungi were considered to be likely candidates.

Several marine dinoflagellates have been shown to produce potent toxins capable of adversely affecting a variety of organisms (Sasner, 1973). For example, the toxin(s) produced by the marine dinoflagellate, Gymnodinium breve, has been directly responsible for massive mortalities of marine organisms in the Gulf of Mexico (Davis, 1948), while a number of human illnesses and deaths have occurred along the Pacific and Atlantic coasts of the United States as a result of the consumption of molluscs containing paralytic shellfish poison (PSP) produced by the dinoflagellates Gonyaulax catenella and G. tamarensis, respectively (McFarren et al., 1956). Halstead (1965) also suspected several other dinoflagellates as producing substances that were potentially toxic to man as well as marine organisms. Interestingly, the list of suspect dinoflagellates included the dinoflagellate, Gymnodinium splendens, and members of the genus, Prorocentrum --- both of which were the predominate dinoflagellates identified in the Liberty Bay algal bloom. In addition to the potentially harmful impact of blooms of toxigenic algae, algal blooms have also created adverse conditions as a result of nutrient imbalance, oxygen deficiency, and hydrogen sulfide production resulting from the decomposition of organic matter and the presence of increased numbers of bacteria (Sasner, 1973).

Although algal blooms have not been directly implicated in previous mortalities of Pacific oyster embryos and larvae, the adverse effect of certain algae, bacteria, and fungi on the early life stages of several other marine bivalve molluscs has been well documented. Davis and Guillard (1958) observed the green alga, Stichococcus sp., and the brackish water golden alga, Prymnesium parvum, to be toxic to the larvae of American oysters, *C. virginica* and hard clams, *M. mercenaria*, when supplied as food. One of the earliest records of bacteria exerting a harmful effect on oyster larvae was that of Davis (1953) who found that bacteria affected both the growth and survival of larvae of the American oyster. Similar observations were made by Walne (1958) using larvae of the European flat oyster, *Ostrea edulis*, and by Guillard (1959) who found isolates of the bacteria *Vibrio* sp. and *Pseudomonas* sp. to be harmful to larvae of hard clams. Davis (1954) also determined that the fungus, *Sirolpidium zoophthorum*, was responsible for the extensive mortality of clam larvae being reared in the laboratory.

Several antibiotics were demonstrated to effectively reduce the harmful effects of certain bacteria and fungi on bivalve larvae. It is significant, however, that as early as 1955, Loosanoff and Davis (1963) found it necessary to treat all seawater and algal food supplies used in the cultivation of bivalve molluscs with ultraviolet (UV) light to reduce the potential adverse impact of associated bacterial and fungal populations. Later, Sinderman and Rosenfield (1967) proposed that disease-related mortalities of invertebrates under cultivation be controlled by a combination of UV and antibiotic treatment of filtered seawater coupled with good sanitation practices, the control of contaminants in algal cultures, and the elimination of intermediate disease hosts.

Before Sea Farms, Inc. closed its oyster hatchery as a result of excessive larval mortalities it had been using a sand filter to remove the larger materials from its incoming seawater supply. It had also applied various antibiotics in an unsuccessful attempt to control the mortalities. Ultraviolet light had not been used, however, to treat its incoming seawater supply or the algal cultures being fed to the larvae under cultivation. Contamination of the larval cultures with ciliate protozoans (peritrichs) known to feed on bacteria was also observed on occasion (Personal Communication, Sea Farms, Inc.).

Marine water quality information collected by the Washington State Department of Fisheries indicates that potential oyster larvae abnormality and mortality problems are not necessarily limited to Liberty Bay or the Sea Farms operation. In the early 1960s concern grew over the increased mortalities of commercially important Pacific oysters in Washington State waters. Westley et al., (1966) reported that natural mortalities of adult Pacific oysters in southern Puget Sound appeared to be associated in some way with fall blooms of the armored dinoflagellate, Ceratium. A similar observation was made by Scholz, Westley, and Tarr (1968). Unable to establish a definite cause and effect relationship, Westley and his associates (1966) recognized the possibility that the organism responsible for the adult mortalities may not have been Ceratium, but some other organism associated with blooms of this alga. More recently, bacteria associated with warm, nutrient-rich waters have been implicated as the cause of these mortalities (Lipovsky and Chew, 1974; Grischkowsky and Liston, 1974).

In conjunction with their work on adult oysters, Westley et al., (1966) also performed oyster embryo assays on selected waters from southern Puget Sound and Hood Canal to determine if oyster embryo response (as measured by embryo development) could be related to the adult mortalities. Larval abnormality was not found to be significantly related to adult mortality, salinity, PBI-sensitive substances, or chlorophyll a. An unexplained decline in some of the larval populations did appear to occur, however, during the 48-hour test period. These population reductions may have resulted from the accidental mechanical loss of individuals during bioassay termination as shown to be possible by Cardwell _et al_., (In preparation). It is also possible, however, that the decline in the numbers of larvae actually reflected larval mortalities that may have been related to conditions associated with algal blooms and the deaths of the adult oysters.

Long-term water quality monitoring by the Department of Fisheries has tended to support the latter possibility. Occasional increases in larval abnormality and mortality rates have been observed in the productive southern Puget Sound waters in question (Eld, Totten, and Budd Inlets) as well as in waters from southeastern Hood Canal, Carr Point, and from Discovery Bay located between the Strait of Juan de Fuca and Admiralty Inlet. The poor embryo or larval responses observed are believed to have been directly related to the microbial populations of the waters tested (Personal Communication, Rick Cardwell, Washington State Department of Fisheries, Brinnon, WA).

Liberty Bay waters assayed by Department of Fisheries personnel from 1962-1975 were characterized by relatively good larval development. Intermittent larval mortalities were observed, however, in surface waters collected near the City of Poulsbo (Personal Communication, Rick Cardwell, Washington State Department of Fisheries, Brinnon, WA). Although the cause of these mortalities was not established, they demonstrate that, at times, certain Liberty Bay waters have been unsuitable for rearing the early life stages of Pacific oysters.

The background information presented above certainly suggests that toxic microbial metabolites or infectious diseases may have contributed substantially to the oyster embryo and larvae mortalities experienced by Sea Farms, Inc. Further investigation would be required, however, to confirm or refute this possibility.

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APPENDIX A

State of Washington, Department of Ecology Standards for Class AA (Extraordinary) Water Quality (State of Washington, 1973).

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(1) Class AA (Extraordinary).

(a) General characteristic. Water quality of this class shall markedly and uniformly exceed the requirements for all or substantially all uses.

(b) Characteristic uses. Characteristic uses shall include, but are not limited to the following:

(i) Water supply (domestic, industrial, agricultural).

(ii) Wildlife habitat, stock watering.

(iii) General recreation and aesthetic enjoyment (picnicking, hiking, fishing, swimming, skiing, and boating).

(iv) General marine recreation and navigation.

(v) Fish and shellfish reproduction, rearing, and harvest.

(c) Water quality criteria.

(i) Total coliform organisms shall not exceed median values of 50 (fresh water) or 70 (marine water) with less than 10% of samples exceeding 230 when associated with any fecal source.

(ii) Dissolved oxygen shall exceed 9.5 mg/1 (fresh water) or 7.0 mg/1 (marine water).

(iii) Total dissolved gas - the concentration of total dissolved gas shall not exceed 110% of saturation at any point of sample collection.

(iv) Temperature - water temperatures shall not exceed 60° F. (fresh water) or 55° F. (marine water) due in part to measurable (0.5° F.) increases resulting from human activities; nor shall such temperature increases, at any time, exceed $t = 75/(T-22)$ (fresh water) or $t = 24/(T-39)$ (marine water); for purposes hereof "t" represents the permissive increase and "T" represents the water temperature due to all causes combined.

(v) pH shall be within the range of 6.5 to 8.5 (fresh water) or 7.0 to 8.5 (marine water) with an induced variation of less than 0.1 units.

(vi) Turbidity shall not exceed 5 JTU over natural conditions.

(vii) Toxic, radioactive, or deleterious material concentrations shall be less than those which may affect public health, the natural aquatic environment, or the desirability of the water for any usage.

(viii) Aesthetic values shall not be impaired by the presence of materials or their effects, excluding those of natural origin, which offend the senses of sight, smell, touch or taste.

APPENDIX B

Relative Point Source Loadings to Liberty Bay (9-15-75 to 9-19-75)

	Sewage Treatment Plants						Total
	Poulsbo		Keyport		Torpedo Station		
Parameter	lbs/d	%	lbs/d	%	lbs/d	%	load (lbs/d)
Flow	0.25 MGD[a]	71	.02 MGD	6	0.08 MGD	23	0.35
Total Solids	1169	69	88.5	5	442	26	1700
Total Suspended Solids	242	82	5.33	2	48	16	295
Total Dissolved Solids	894	68	68	5	352	27	1314
Total Coliforms	1100/100 ml	-	<18/100 ml	-	4600/100 ml	-	-
MBAS[b]	12.6	99	0.02	0.2	0.07	0.6	12.69
Total Phosphorus	26.3	81	2.22	7	4.13	13	32.65
Ammonia Nitrogen	52.08	89	0.117	0.2	6.27	11	58.5
Total Metals							
Cd	0.0116	12	0.0018	2	0.0868	87	0.1
Cr	0.0279	3	0.0013	0.1	0.994	97	1.023
Hex Cr.	-	-	-	-	0.0199	100	-
Cu	0.0792	48	0.0115	7	0.0749	45	0.166
Pb	0.0815	68	0.005	4	0.0342	28	0.121
Hg	0.0007	46	0.000033	2	0.0008	52	0.002
Ni	0.198	3	0.0042	0.1	5.95	97	6.15
Zn	0.442	56	0.117	15	0.227	29	0.786

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[a] MGD - million gallons per day
[b] MBAS - methylene blue active substances

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